



Commercial Space Technology Roadmap

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Executive Summary

This Commercial Space Technology Roadmap document is delivered as a companion to the report titled, “Project Final Report: Development of a Commercial Space Technology Roadmap”. The report document details the motivation for such a roadmap as well as the high level methodology employed for the process, while this document puts it into practice. We present several case studies applying the developed methodology to particular sub-sectors of the Space Economy in order to generate commercial technology roadmaps. The sub-sectors investigated here, chosen from those identified as part of the Market Sector Breakdown, represent a cross-section of the space economy, from traditional and established sectors (e.g. Launch Services) to novel and nascent sectors (e.g. In-Space Manufacturing and Planetary Surveying, Mapping and Prospecting). Indeed, this effort found that significant commercial activity, often supported by NASA expertise and funding, is working to transform even those established sub-sectors. Further, barriers to commencing private activity within new and emerging sectors (like On-Orbit Servicing) can similarly be lowered through NASA and other public investments or incentives.

The analyses are generally conducted at the sub-sector level, though sector-level analyses can also be conducted or aggregated from sub-sector analyses. The sub-sectors investigated here include:

1. Launch Services (within the Space Transportation and Access sector)
2. In-Space Manufacturing Systems and Services (within the On-Orbit Services sector)
3. GPS Systems (within the Navigation and Positioning sector)
4. Earth Imaging/Sensing (within the Remote Sensing sector)
5. Planetary Surveying, Mapping and Prospecting Services (within the Resource Extraction sector)

Analyses begin by defining the sub-sector boundaries (i.e. what does and does not count as commercial activity within that sub-sector), a representative set of players active in the area, and their key products. The stated goals and technological needs of these companies (as captured in publicly available information) are then synthesized into sub-sector wide strategic thrusts and sub-thrusts quantifiable through key Figures of Merit (FOM) trends and targets. Information on technology development, product timelines, and FOMs is converted to analysis products which capture salient insights for each sub-sector. We do not claim company or technology exhaustiveness. Where possible, as many companies as are active are considered, but in particularly large sectors, such as Launch Services, exhaustiveness is infeasible. Similarly, only key technologies are identified for each product - that is, technologies integral to the delivery of a value-adding function by a product. Capturing every technology present in a product would be similarly infeasible.

The case studies described in this document may be viewed as a first step towards capturing the technological needs of the commercial space economy. The template for sub-sector technology roadmapping implemented here may be employed across the remaining sectors and sub-sectors to develop an even more in-depth understanding of the technologies, paradigms, and interdependencies which impact the growth and future of the Space Economy. It can help NASA accomplish several tasks including: 1) maintaining an active repository of the “State of the Commercial Space Economy”, 2) understanding how its technological needs and development projects align with those of commercial space and 3) identifying areas where collaboration with industry can yield symbiotic benefits. This should be seen as the beginnings of a dynamic and living database, kept up-to-date with the most recent developments and the emergence of new technologies and sectors within the space economy.

Commercial Space Economy Market Sector Breakdown

A high level, logical breakdown of the current (and envisioned near-future) commercial space economy is presented below, including nine major market sectors. The first four sectors operate directly on space missions – including their development, launch, operation and maintenance. The next four sectors capture activities that provide services to Earth-based customers through space missions – including communications, navigation, and remote sensing. Lastly, a set of services were identified which could not be classified under any one of the defined categories but are nevertheless critical to space missions – these include robotics systems and services, space technology R&D, data processing, and insurance services. The table below further breaks down each market sector into sub-sectors to support analysis with higher resolution.

| Sector | | Sub-sector | |
|--------|--|------------|--|
| 1 | Space Transportation and Access | 1.1 | Launch Services (manned/unmanned, exploration/tourism) |
| | | 1.2 | Habitation Systems and Services |
| | | 1.3 | In-Space Transportation Systems and Services |
| | | 1.4 | Planetary Entry, Descent, and Landing (EDL) Systems and Services |
| 2 | Spacecraft Development and Manufacturing | 2.1 | Subsystem Design |
| | | 2.2 | Subsystem Manufacturing |
| | | 2.3 | Spacecraft Integration |
| | | 2.4 | Spacecraft Assembly |
| | | 2.5 | Spacecraft Testing |
| 3 | Ground Sites | 3.1 | Launch Sites |
| | | 3.2 | Tracking |
| | | 3.3 | Satellite Operations |
| 4 | On-Orbit Services | 4.1 | In-Space Manufacturing Systems and Services |
| | | 4.2 | On-Orbit Servicing |
| | | 4.3 | Orbital Debris Tracking and Removal Systems and Services |
| 5 | Telecommunications Services | 5.1 | Fixed Satellite Services |
| | | 5.2 | Broadcast Satellite Services |
| | | 5.3 | Mobile Satellite Services |
| 6 | Navigation and Positioning Services | 6.1 | Global Positioning System (GPS) |
| 7 | Remote Sensing Services | 7.1 | Earth Imaging/Sensing |
| | | 7.2 | National Security Related Products and Services |
| | | 7.3 | Science Instruments and Services |
| 8 | Space Resource Extraction | 8.1 | Planetary Physical Surveying, Mapping, and Prospecting Services |
| | | 8.2 | Extraction and Processing of Water and Volatiles |
| | | 8.3 | Extraction and Processing of Metals, Minerals, and Ores |
| 9 | Support Industries | 9.1 | Robotics Systems and Services |
| | | 9.2 | Research and Development Services |
| | | 9.3 | Data Processing, Storage, Dissemination Systems and Services |
| | | 9.4 | Insurance of Space Systems |

For each of these identified sub-sectors, detailed technology roadmapping and analysis can be performed. In this particular document, the results of analysis for the following selected set of sub-sectors is presented: 1.1 Launch Services, 4.1 In-Space Manufacturing Systems and Services, 6.1 Global Positioning System (GPS), 7.1 Earth Imaging/Sensing, and 8.1 Planetary Physical Surveying, Mapping, and Prospecting Services. Figure 1 below provides an overview of the distribution of technology focus across the sub-sectors considered. The bar chart reports the number of instances in which a given technology serves as a key technology for a product line from selected major industry players in a given sub-sector. The technology numbers presented in this table refer to those in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report. Sub-sectors differ in terms of the breadth of their technology focus, and in the number of products with a given key technology. Cases of mutual interest and expertise in a technology area across multiple sub-sectors can prove particularly interesting for direct technology development benefits to numerous sectors.

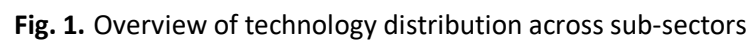


Fig. 1. Overview of technology distribution across sub-sectors

Market Sector Interdependencies

Sub-sector interdependencies are modeled under the principle that the infusion of technology in a sub-sector changes the state of key figures of merit for cost, performance, and safety. These state changes in upstream sectors then differentially impact the state and rate of development of important cost, performance, and safety figures of merit of various downstream sectors. A matrix depicting these interdependencies between all 29 sub-sectors is shown, Figure 2 below. For a given entry in the matrix, the sub-sector in that row is the upstream sector providing benefits to the sub-sector in that column, which is the downstream sub-sector.

Understanding these market sector interdependencies is critical to effective public-private technology planning. Such a plan endogenizes and targets growth dynamics in the commercial space economy by identifying the potential for each technology to contribute to improvements not only in its primary sector of application, but also indirectly in other sectors. For example, improvements in the cost, performance, and safety of launch services are likely to accelerate the growth of other downstream sectors and sub-sectors, such as telecommunications, remote sensing, space tourism, space resource extraction, and in-space manufacturing. This critical impact of decreasing launch costs to downstream sectors is highlighted in Figure 2 with light yellow.

However upon investigating why the launch costs are falling, we find that upon the announcement of Commercial Orbital Transportation Services opportunity, NASA had positioned itself as a guaranteed customer in the downstream sector 1.2 'Habitation Systems and Services'. This created a demand for launch services which, over time, led to technology development, learning, investment and falling costs in the Launch Services sub-sector, all led by the 'New Space' companies which seized the COTS opportunity offered by NASA. These same companies are now revolutionizing the sector of spacecraft development and manufacturing, resulting in far-reaching cost, performance and/or safety impacts to 17 different sub-sectors of the space economy (green highlight in Figure 2).

In due course, once the low-hanging fruit of cost reductions and performance improvements via reusability is taken, the rocket equation will eventually raise a barrier to further cost reductions or performance improvements in launch services, threatening to arrest the further growth of the space economy. This barrier can be circumvented by the future impact of in situ resource utilization (ISRU) and in space manufacturing (ISM) technologies, highlighted in light red in Figure 2.

This analysis shows that over the long term, the interactions between falling launch costs, advances in spacecraft development and manufacturing, and advances in ISRU and ISM, will be the main source of staying power leading to continuous improvements in the key performance indicators for most sectors in the space economy. As a result, the space economy will be poised to grow at above-normal rates for as long as this dynamic continues. As the space economy grows, sub-sectors grow and develop, creating natural demand and supply for new technologies which is met by market participants.

In summary, therefore, the strategic challenge for NASA is to choose the sectors, timing and means of investment in technology development so as to maximize the future growth of the overall space economy.

| Propagation of KPI impacts from current to future space economy subsectors resulting from technology development and infusion | | | 1.1 | 1.2 | 1.3 | 1.4 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 3.1 | 3.2 | 3.3 | 4.1 | 4.2 | 4.3 | 5.1 | 5.2 | 5.3 | 6.1 | 7.1 | 7.2 | 7.3 | 8.1 | 8.2 | 8.3 | 9.1 | 9.2 | 9.3 | 9.4 |
|---|--|-----|--|-----|-----|-----|-----|--|-----|-----|-----|-----|-------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Space Transportation and Access | Launch Services: unmanned/manned, exploration/tourism | 1.1 | | C | C | | CP | | | | | | | C | C | C | C | C | C | C | C | C | C | C | C | C | C | | | | C |
| | Habitation Systems and Services | 1.2 | | | | | | | | | | | | | CP | CP | | | | | | | P | | | | CP | | | | |
| | In-Space Transportation Systems and Services | 1.3 | | CS | | | | | | | | | | | CPS | CPS | CP | | | | | | | | | CPS | CPS | CPS | | | |
| | Planetary Entry, Descent, and Landing (EDL) Systems and Services | 1.4 | C | PS | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Spacecraft Development and Manufacturing | Subsystem Design | 2.1 | CPS | CPS | CPS | CPS | | C | | | | | | | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | | | |
| | Subsystem Manufacturing | 2.2 | C | C | C | C | | | C | P | | | | | C | C | C | C | C | C | C | C | C | C | C | C | C | C | | | |
| | Spacecraft Integration | 2.3 | CPS | CPS | CPS | CPS | | | | | P | | | | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | CPS | | | |
| | Spacecraft Assembly | 2.4 | C | C | C | C | | | C | | | | | | C | C | C | C | C | C | C | C | C | C | C | C | C | C | | | |
| | Spacecraft Testing | 2.5 | S | S | S | S | | | C | | | | | | S | S | S | S | S | S | S | S | S | S | S | S | S | S | | | |
| Ground Sites | Launch Sites | 3.1 | PS | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Tracking | 3.2 | S | | | | | | | | | | | | | | | P | | | | | | | | | | | | | |
| | Satellite Operations | 3.3 | | | | | | | | | | | | | | | C | C | C | C | C | | | | | | | | | | |
| On-orbit Services | In-Space Manufacturing Systems and Services | 4.1 | | CPS | CPS | | CP | CPS | CP | CP | | | | | | | | | C | C | C | | | | | CPS | CPS | CPS | | | |
| | On-orbit Servicing | 4.2 | | CPS | CPS | | CP | CP | CP | CP | | | | | | | | | C | C | C | C | C | C | C | | | | | | |
| | Orbital Debris Tracking and Removal Systems and Services | 4.3 | S | S | | | | | | | | | | | S | S | S | S | S | S | S | S | S | S | | | | | | | |
| Telecom Services | Fixed Satellite Services | 5.1 | | | | PS | | | | | | | P | | | | | | | | | | | | | P | | | | CP | |
| | Broadcast Satellite Services | 5.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Mobile Satellite Services | 5.3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Nav | Global Positioning System (GPS) | 6.1 | | | | | | | | | | | | | | | | | | | | | P | | | | | | | | |
| Remote Sensing Services | Earth Imaging/Sensing | 7.1 | | | | | | | | | | | | | | | | | | | | | P | | | CP | | | | | |
| | National Security Related Products and Services | 7.2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Science Instruments and Services | 7.3 | | | | | | | | | | | | | | | | | | | | | | | | P | | | | | |
| Space Resource Extraction | Planetary Physical Surveying, Mapping, and Prospecting Services | 8.1 | | PS | | PS | | | | | | | | | | | | | | | | | | | | | CP | CP | | | |
| | Extraction and Processing of Water and Volatiles | 8.2 | | CP | CP | CP | | | | | | | | | CP | CP | CP | | | | | | | | | | CP | CP | | | |
| | Extraction and Processing of Metals, Minerals, and Ores | 8.3 | | C | C | | | | | | | | | | CP | CP | | | | | | | | | | | | | | | |
| Support Industries | Robotics Systems and Services | 9.1 | | | | | | | | | | | | | CP | CP | PS | | | | | | | | | CP | CP | CP | | | |
| | Research and Development Services | 9.2 | CPS | CPS | CPS | CPS | | | | | | | | | CPS | CPS | CPS | | | | | | CP | CPS | CPS | CPS | CPS | | | | |
| | Data Processing, Storage, and Dissemination Systems and Services | 9.3 | | | | | | | | | | | | | | | | P | P | P | P | P | P | P | | | | | | | |
| | Insurance of Space Systems | 9.4 | C | | | | | | | | | | | | | C | C | C | C | C | C | C | C | C | C | C | C | C | | | |
| Key to highlights: | | | critical impact of decreasing launch costs | | | | | critical impact of 'new space' on spacecraft dev | | | | | future impact of ISRU and ISM | | | | | | | | | | | | | | | | | | |
| Key: Cost Performance Safety | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

Fig. 2. Propagation of Key Performance Indicator (KPI) Impacts from Current to Future Space Economy Sub-Sectors Resulting From Technology Development and Infusion. Rows represent the current state, columns the future state and the matrix entries C, P and S represent Cost, Performance and Safety impacts respectively. (Note of limitations: full case studies for all 29 space economy sub-sectors would be required to derive a validated matrix. The impacts shown above represent the opinion of the authors based on the in-depth study of only 5 sub-sectors)

Sub-sector #1.1: Launch Services

Sub-sector Overview

The launch services industry includes all companies that provide a capability to transport mass from the surface of the Earth into orbit. Commercial launch is an interesting sector for analysis because of the recent growth in the field through NASA involvement in programs such as COTS and CCDev [1,2]. In addition, launch services is an important market sector due to the key performance indicator impacts to other sectors as all orbital operations require a launch. Thus, benefits in launch services tend to flow downstream as benefits for other sectors of the space economy. Technology development in this sub-sector focuses on rocket engines, structural systems, payload interfaces, GNC systems, and recovery/reuse operations. These technology developments are pursued for both traditional launch vehicles and novel designs, such as air-launch architectures.

The launch services industry is a large, growing, and active commercial sector. The U.S. launch industry is a \$2.2B sector making up approximately 40% of global revenues. Internationally, the U.S. has the largest fraction of commercial launch revenues [3]. When analyzing the launch services industry, it is important to identify the state of growth as well as the relative strength of the U.S. industry. This information can be ascertained from the Federal Aviation Administration Associate Administrator for Commercial Space Transportation (FAA-AST) *Commercial Space Transportation Year In Review* and *Annual Compendium of Commercial Space Transportation* reports [4,5]. Fig. 1.1.1 shows the trend in number of U.S. launches over time. We can see that there has been a recent general trend of resurgence in number of launches and fraction of commercial launches since the announcement of NASA's Commercial Orbital Transportation Services (COTS) program in 2006. We can see, in Fig. 1.1.2, that over this time period there has also been an upward trend in number of global launches, but that the increasing commercial launch fraction is unique to the U.S. space industry, which provides a good opportunity for commercial technology development. An even stronger trend is seen in the number of orbital payloads launched, as shown in Fig. 1.1.3, due to the rise of small satellites. A significant increase in total number of payloads and U.S. involvement has been seen since 2011 timeframe. At present, up to 90% of commercial payloads are launched by the U.S. However, as more countries develop launch capabilities, U.S. companies will begin to face pressure from global competition.

The relative strength of the U.S. launch industry is seen even more clearly by considering global launch revenues, as shown in Fig. 1.1.4. Since 2006, and most notably after 2011, the U.S. space industry has shown significant increase in revenue, resulting in a nearly 50% share of global orbital launch revenues. Thus, the presence of a vibrant commercial launch industry can both be seen as an indication of the benefits of a commercial program like COTS, as well as an indication of the potential for this vibrant industry to continue to develop technologies for, or alongside, NASA.

An even stronger indication of the success of the COTS program is seen by considering the change in the specific launch cost to LEO after the implementation of the COST program. As shown in Fig. 1.1.5, prior to the COTS program, industry launch vehicles cost on average \$13,600/kg to LEO, whereas recent COTS vehicles have reduced their cost to on average \$5,600/kg. This has driven other players in the launch industry to begin development of lower cost launchers.

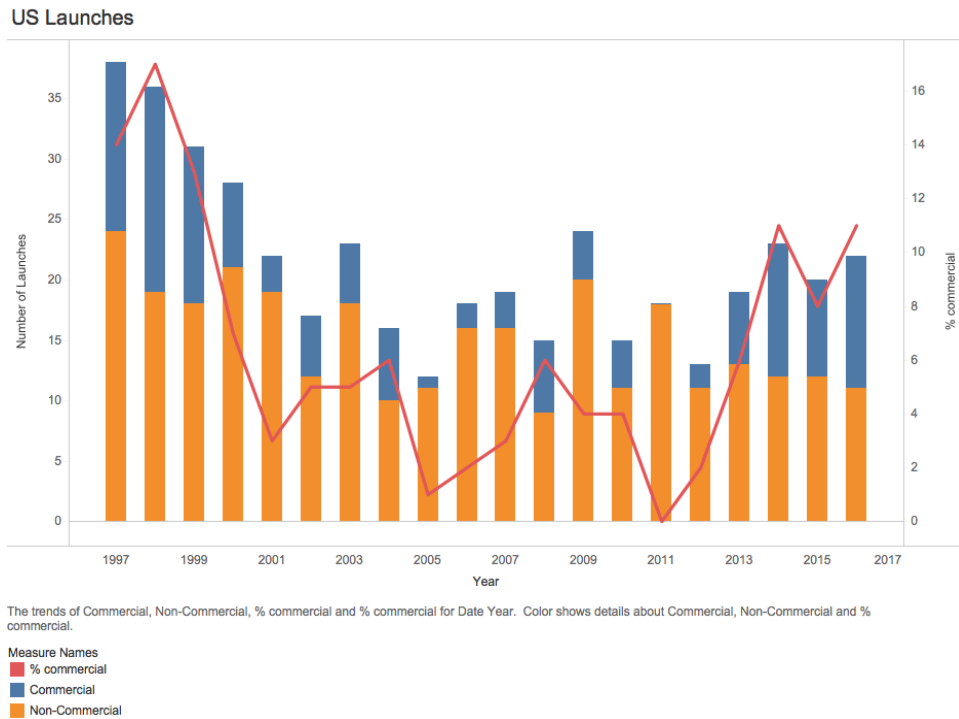


Fig. 1.1.1. U.S. launch trends from 1997 to 2017.

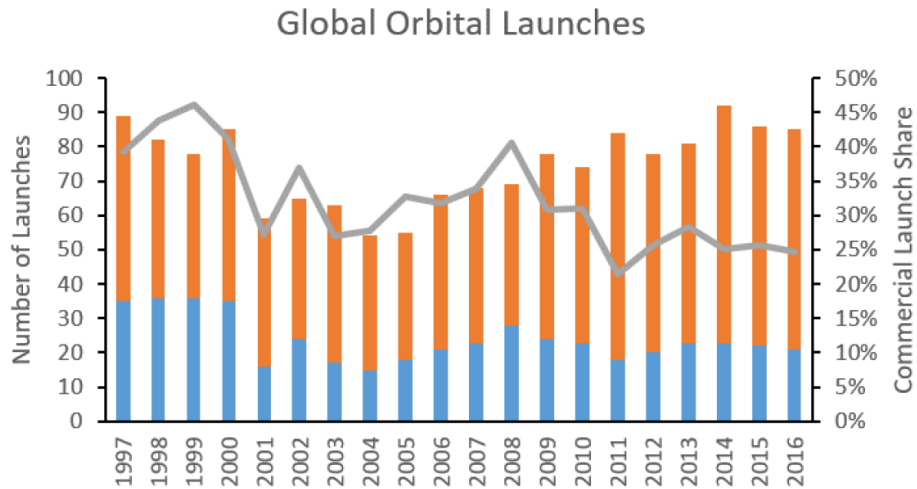


Fig. 1.1.2. Total global orbital launches and payloads from 1997 to 2016, categorized as commercial or non-commercial. The percentage of launches/payloads that are commercial is indicated by the gray line.

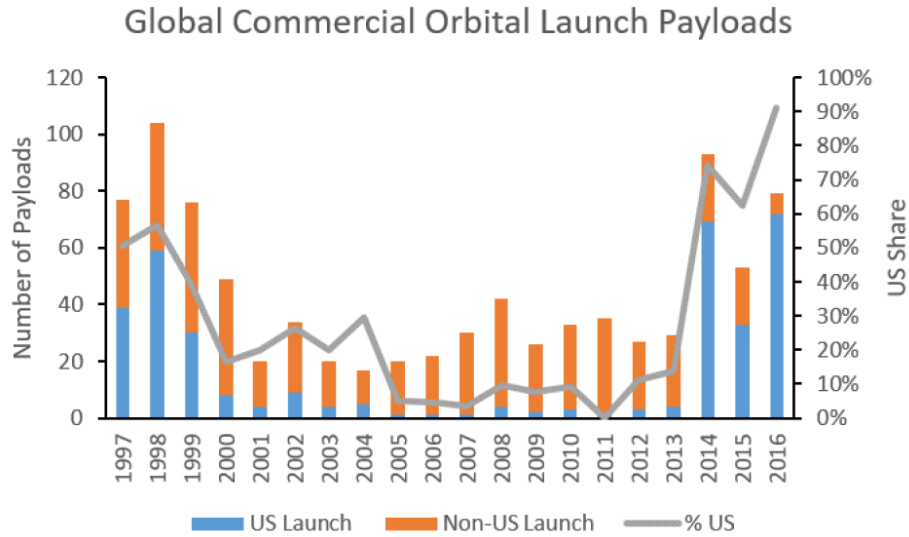


Fig. 1.1.3. Global commercial orbital payloads from 1997 to 2016, categorized by launching country (US or non-US). The percentage of payloads launched by US vehicles is indicated by the gray line.

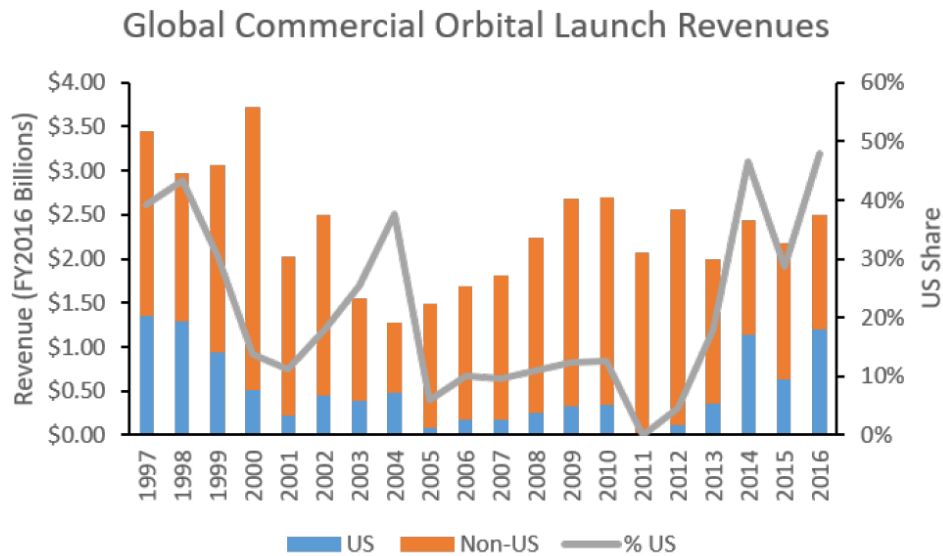


Fig. 1.1.4. Global commercial orbital launch revenues from 1997 to 2016, categorized by launching country (US or non-US). The US market share is indicated by the gray line.

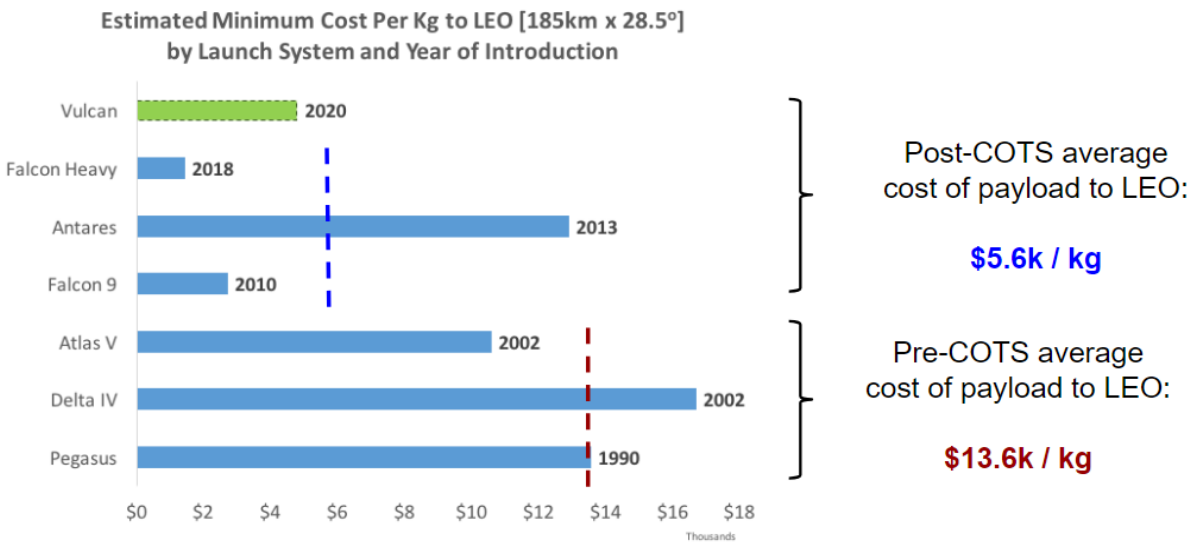


Fig. 1.1.5. Specific launch cost to LEO in the pre- and post-COTS eras, broken down by launch vehicle.

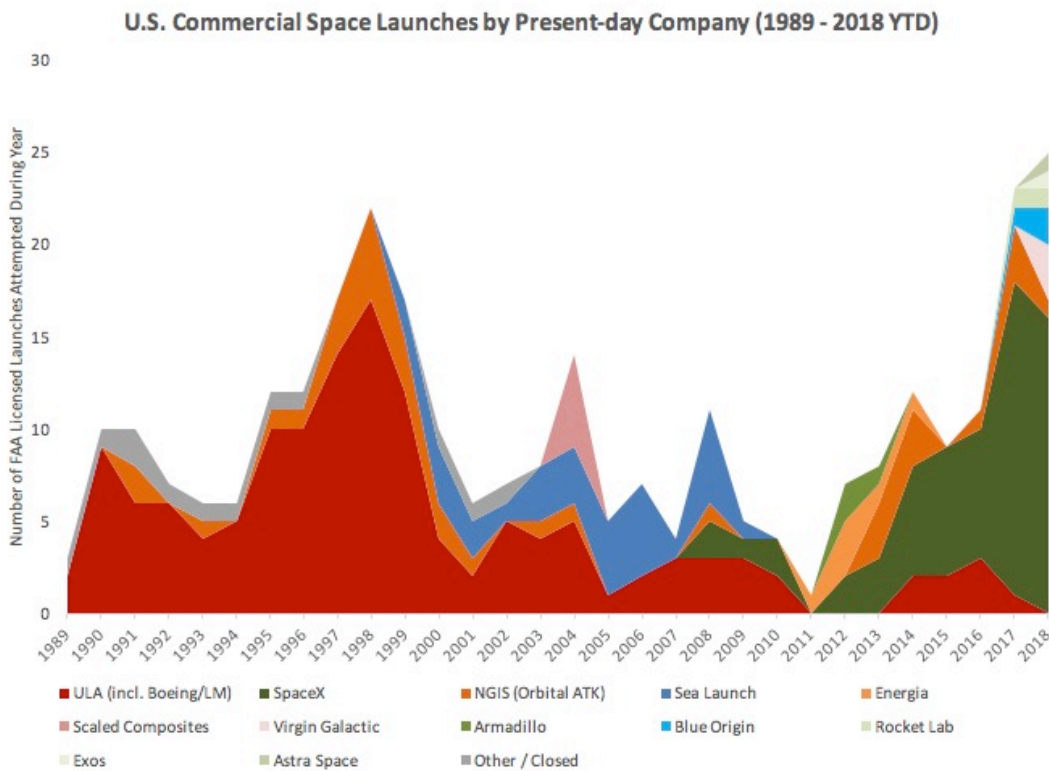


Fig. 1.1.6. Number of commercial space launches per year in the US, broken out by company. Commercial is defined as any launch requiring a FAA license. Throughout the 1990's, the market was dominated by companies which were rolled up into ULA in 2006. Since 2008, SpaceX has emerged as the market leader in commercial launch services. New entrants have also emerged in recent years. Data source: FAA [6]

When making technology investment decisions for the commercial launch industry, knowledge of the companies involved in the sector is needed. In Fig. 1.1.6, we see again that the number of commercial launches has shown a recent upward trend. In addition, there appears to be an evolving dynamic of which companies are most active in launch, whether due to new entries into the market or via mergers and acquisitions, which are prevalent in the industry. Over time, different companies come to the forefront and dominate the number of commercial US launches. This can lead to changing priorities and desire for technology development in commercial industry that must be tracked and considered.

Sub-Sector Interdependencies

The Launch Services sub-sector directly influences the cost of 18 out of the 29 identified space economy sub-sectors. In turn, the cost, performance and safety of launch services are influenced by spacecraft development and manufacturing, ground operations, orbital debris tracking and removal, general R&D and insurance of space systems. These interdependencies are visualized in the diagram, Fig. 1.1.7 below.

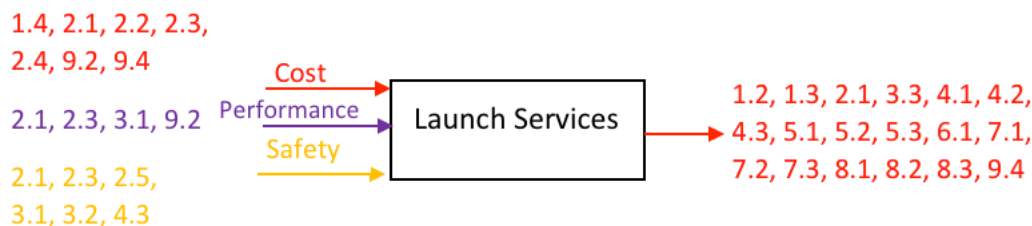


Fig. 1.1.7. Interdependencies between Launch Services sub-sector and upstream, downstream commercial space economy sub-sectors

Starting from the left hand side, sectors upstream of launch, such as 2.1 to 2.5 (spacecraft development and manufacturing), 3.1, 3.2 (ground sites) and 9.2, 9.4 (other support industries) undergo changes in their key performance indicators as a result of technology development and infusion. These changes then result in the propagation of cost, performance or safety impacts to the downstream launch services sector. As the cost per launch falls, and payload to orbit and reliability increase, the specific cost of delivering payload to orbit falls. This improvement in the key Figure of Merit of launch services transmits the economic impact of technology development from upstream to downstream sectors. In the case of launch, the set of downstream sectors includes every in-space activity in the space economy. Clearly, launch services is the sub-sector which holds the key to the development of every in-space sector, but this is a trivial insight. The real insights uncovered by focusing on the transmission mechanism of the economic impacts of technology development are that technology development in downstream sectors can be induced by the *indirect means* of investing in technology development in an upstream sector, and relying on competitive growth dynamics to propagate the benefits downstream. It also illustrates that technology development in upstream sectors can be induced by the indirect means of NASA occupying a downstream sector for a predefined period of time and assuming the role of guaranteed blue-chip customer. An example of the latter is the Commercial Orbital Transportation Services (COTS) program.

Strategic Thrust and Figures of Merit

In the launch services industry, the value-adding process is transporting mass from Earth to space. To add economic value in this sector, the value-adding process must be performed well. Several attributes that capture the quality of transporting mass from Earth to space are the following: reducing cost, improving safety, increasing interoperability of launchers and payloads to reduce market frictions, improving launch cadence, improving responsiveness, and meeting customer needs (i.e. payload volume, mass, destination orbit, and launch environment). These attributes were determined based on knowledge of the function of the launch services industry as well as company's current development activities. Based on this information, the strategic thrust for the launch services industry is identified to be:

Provide cheaper, safer, and more timely transportation of mass from Earth to space while meeting payload needs.

This strategic thrust captures the direction in which technology developments should aim to push the launch services industry. This strategic thrust is a solution-neutral description aimed at capturing the goals of the launch services sector. The strategic thrust can be thought of as a description of the utopia point used to identify a Pareto front of potential solutions. Technology areas will subsequently be identified by flowing down from the solution-neutral strategic thrust to capture current and potential future activity in the sector.

Quantifiable metrics, or figures of merit, are now developed to identify how well the strategic thrust is achieved under various technology development paths. These metrics and their flowdown from the strategic thrust are shown in Table 1.1.1 below. A given company's emphasis on any one of these sub-thrusts depends on their business model. For example, the sub-thrusts for responsiveness and meeting of payload needs take on new meaning, and in fact are presented as a key selling point, for developers of dedicated small satellite launchers compared to the traditional launch as a secondary payload.

Patent Application Activity

A patent database search was conducted for the launch services industry to identify commercial interest and activity over time, while also identifying the technology areas in which interest is present. This patent searching serves as a preliminary check on the identified key technology areas and reveals the trend in industry's technology focus pertaining to launch vehicles. The trend in total number of patent applications for launch vehicle related technologies is shown in Fig. 1.1.8. A significant uptick in patent applications is seen after the Commercial Space Act of 1998 as well as persistent growth since the announcement of NASA's Commercial Orbital Transportation Services (COTS) program in 2006. Fig. 1.1.9 shows the trend in patent applications over time characterized by international patent classification (IPC) sub group for launch vehicle related patents. This allows for identification of the technology focus of the commercial activity in the launch services sector, which serves as an indicator supplementing a company's publicly stated plans, of commercial desire to invest and develop those technologies. Most patents are seen in IPC sub group B64G1/00, cosmonautic vehicles. Other subgroups have shown varying levels of relative importance over time.

Table 1.1.1: Launch Services Sector Strategic Thrusts and Figures of Merit

| Strategic Thrust: Provide cheaper, safer, and more timely transportation of mass from Earth to space while meeting payload needs. | | |
|--|--|---|
| Strategic Sub-Thrusts | Figure of Merit | Influential Technology Areas (Importance) |
| Reduce launch cost | Specific launch cost (\$/kg) | <i>(Total launch cost divided by payload mass)</i> |
| | Total launch cost (\$) | Propulsion (High) Vehicle Manufacturing (High) Reusability (High) Launch Operations (Med) Ground Support Equipment (Med) Structures (Med) Mechanisms (Low) GNC (Low) |
| Improve safety | Launch success rate (%) | Propulsion (High) Mechanisms (Med) GNC (Med) Structures (Low) |
| Increase launch cadence | Launch rate (#/yr) | Reusability (High) Vehicle Manufacturing (High) Launch Operations (Med) Licensing and Range Availability (Med) Ground Support Equipment (Low) |
| Improve responsiveness | Delay from contract signing to launch (days) | TBD |
| Meet payload needs | Fairing volume (m ³) | Structures (Med) Mechanisms (Med) |
| | Mass to LEO, GTO, GEO, escape (kg) | Propulsion (High) Structures (High) Launch Operations (Low) Ground Support Equipment (Low) |
| | Orbits achievable | Propulsion (High) Launch Operations (Med) Ground Support Equipment (Med) Thermal Control (Med) Avionics (Med) Power (Med) GNC (Low) Communications (Low) |
| | Acceleration (m/s ²) | Propulsion (Med) GNC (Low) Structure (Low) |
| | Random vibration (g ² /Hz) | Propulsion (Low) Structure (Low) |
| | Acoustic pressure (OASPL) | Propulsion (Low) Structure (Low) |
| | Interoperability present: yes/no | TBD |

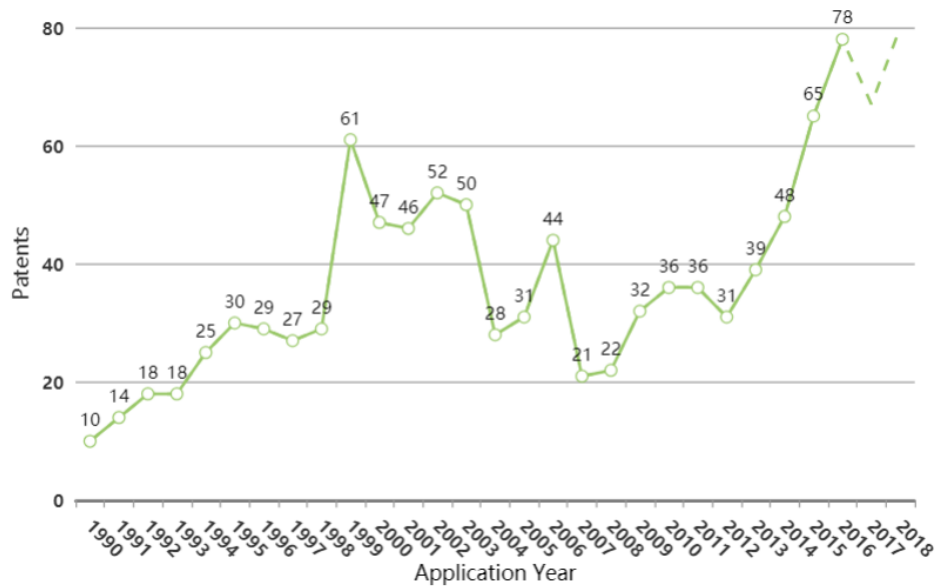


Fig. 1.1.8. The trend in launch vehicle related patent applications over time. The results shown are for the following Patsnap query: TA:("launch* vehicle").

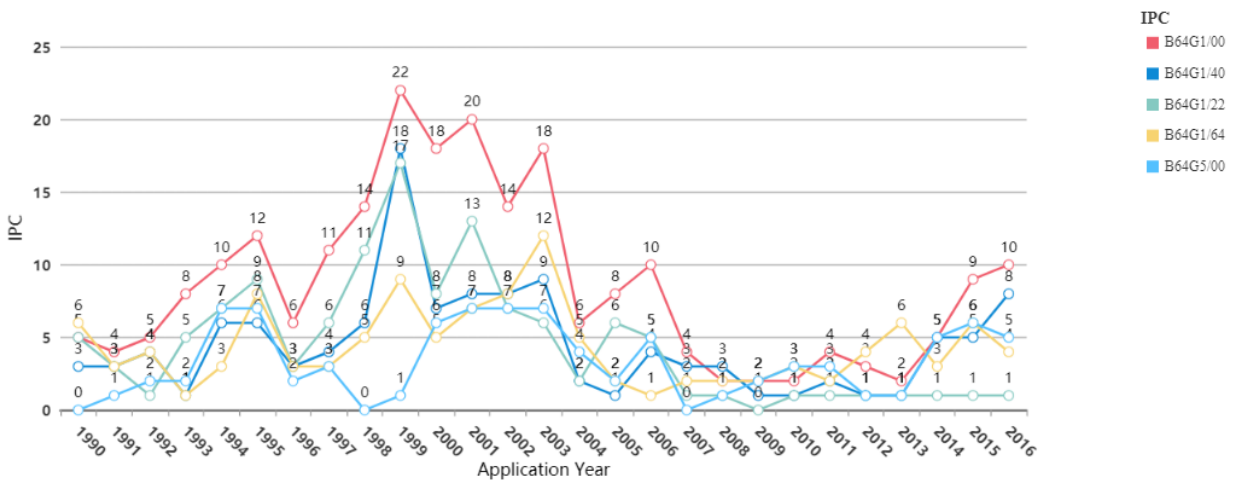


Fig. 1.1.9. The trend in patent applications over time characterized by international patent classification (IPC) sub group for launch vehicle related patents. The results shown are for the following Patsnap query: TA:("launch* vehicle").

Government Investment

The level of NASA involvement and interest in technology development for commercial launch services can be tracked through funding programs such as Commercial Crew Development (CCDev), Commercial Crew Integrated Capability (CCiCap), Commercial Crew Program (CCP), and Commercial Crew Transportation Capability (CCtCap). Identification of the funding provided through these programs serves to indicate NASA's interest level in various commercial technologies, as well as the historical impact of technology investment on commercial developments. The listing of contract awards under CCDev, CCiCap, and CCP is provided in Table 1.1.2 below.

Table 1.1.2: NASA Investment in Commercial Launch Services through CCDev, CCIcap, CCP, and CCtCap

| Year | 2010 | 2011 | 2012 | | 2014 |
|---------------|---------------|------------------|-----------------|---------------|---------------|
| Contract Type | CCDev1 | CCDev2 | CCIcap | CCP | CCtCap |
| ATK | | N/A ¹ | | | |
| Blue Origin | \$3.7 million | \$22 million | | | |
| Boeing | \$18 million | N/A | \$460 million | \$10 million | \$4.2 billion |
| EAI | | N/A | | | |
| Paragon | \$1.4 million | | | | |
| Sierra Nevada | \$20 million | N/A | \$212.5 million | \$9.9 million | |
| SpaceX | | \$500 million | \$440 million | \$9.5 million | \$2.6 billion |
| ULA | \$6.7 million | N/A | | | |

Selected Companies and Associated Product Lines

Following the established methodology, major industry players in this sector were identified. The selection of companies (in alphabetical order) includes: Blue Origin, Exos, Orbital ATK, Rocket Lab, SpaceX, ULA, and Virgin Orbit. For each of these companies their major existing (or planned) product lines, in this case launch vehicles, were identified. For example, for SpaceX the vehicles considered included Falcon 9, Falcon Heavy, and the Big Falcon Rocket. For a selection of these companies and their product lines, the historical first launch date for existing vehicles, or the publicly announced expected first launch date for new vehicles, were compiled and reported in Fig. 1.1.10. A more exhaustive listing of the results of this effort are presented in Table 1.1.3.

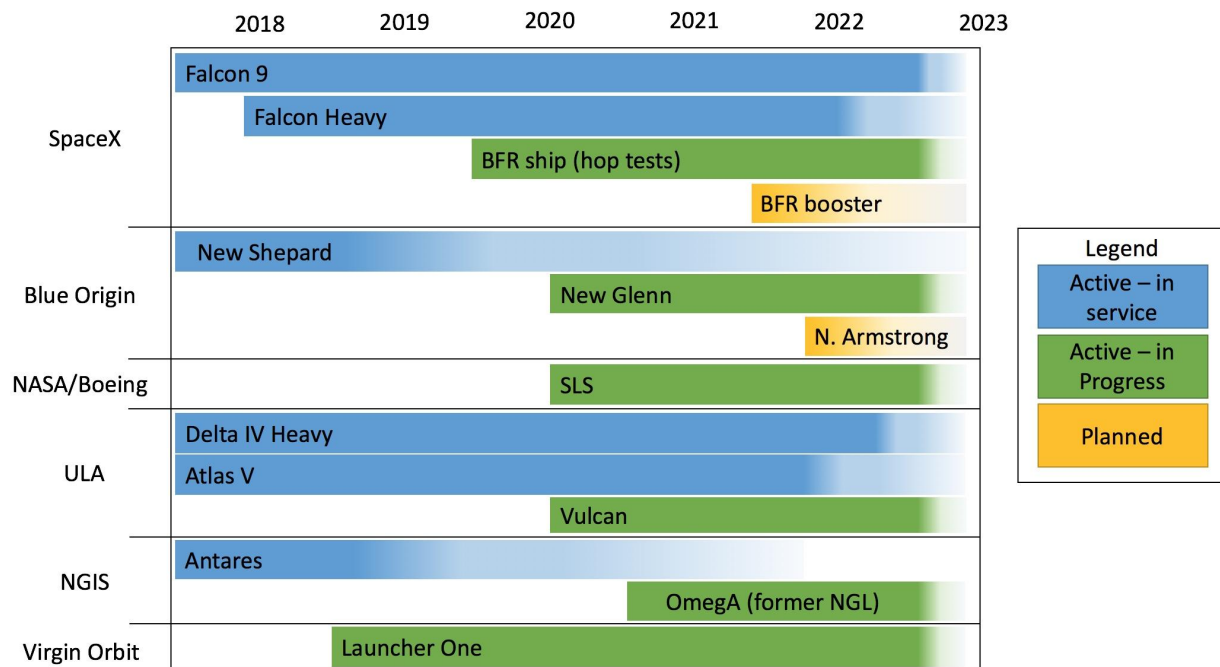


Fig. 1.1.10. Timeline of first launch dates for selected companies and product lines. Understanding of currently active and future planned vehicles and their technology needs is a necessary precursor to effectively promoting and utilizing industry, as well as identifying cost-sharing technology development opportunities.

¹ N/A indicates contract awarded, but funding not disclosed

Table 1.1.3: Selected Launch Services Companies and Associated Products

| Company (Founded) | Product | Timeline |
|----------------------------------|--|--|
| Blue Origin (2000) | New Shepard | Nov. 2015: first flight Jan. 2016: first reuse flight |
| | New Glenn | Sept. 2017: \$2.5B invested in development 2020: anticipated first flight |
| | New Armstrong | TBD |
| Exos (2015) | Sarge | Dec. 2012: predecessor vehicle first flight |
| Orbital ATK (2014) | Pegasus | 1990: first flight |
| | Minotaur | 1994: first flight |
| | Antares | 2013: first flight |
| | Graphite Epoxy Motor (GEM) Strap-on Booster | 1990: first flight |
| | Space Launch System (SLS) Solid Rocket Boosters | 2020: anticipated first flight |
| | Next Generation Launch System | 2021: certification flight |
| Rocket Lab (2006) | Electron | 2017: first flight |
| SpaceX (2002) | Falcon 9 | Jun. 2010: first flight Mar. 2017: first reuse flight |
| | Falcon Heavy | Feb. 2018: first flight |
| | Big Falcon Rocket (BFR) | 2025: anticipated first flight |
| United Launch Alliance (2006) | Delta IV | 2002: first flight |
| | Atlas V | 2002: first flight |
| | Vulcan | 2020: anticipated first flight |
| Virgin Orbit (2017) | Launcher One | 2018: anticipated first flight |

Technology Area Synthesis

Based on the key technologies being pursued by commercial industry product lines, a technology area breakdown structure can be developed. The technologies pertaining to the Launch Services sub-sector are included in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report. In this breakdown, the companies’ specific key technologies form the basis of the level 3 technology areas. The level 1 and 2 technology areas can then be abstracted from the key technology interests of commercial industry, as well as for NASA, to ensure collective exhaustiveness of the technology breakdown. The level 1 technology areas are seen to map into the strategic sub-thrusts for the sector (via Table 1.1.1), which indicates that creative, new technology developments by commercial industry in this sector can be captured by this framework as they arise.

Key Technology Distribution

Throughout this section, technology numbers refer to those in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report.

After identifying the key technologies associated with each product line for each company, the following analysis of results was conducted to identify trends in technology development interest across the sub-sector.

Sector Focus:

First, we can look at which technologies are actively developed in this sector and how prevalent each technology is across the range of product lines in this sector. As seen in Fig. 1.1.11 below, technology development in this sector is spread across the following technology areas: TA 1: Propulsion Systems, TA 2: Structures, TA 3: Mechanisms, TA 4: Thermal Control, TA 5: Avionics, TA 6: GNC and ADCS, TA 7: Power, TA 9: Manufacturing, and TA 10: Ground Segment. The most prevalent technologies, as shown in Table 1.1.4 below, are launch separation systems, stage separation systems, reaction control actuators, and inertial measurement sensors. The next most prevalent technologies are fairing separation, spacecraft deployment systems, and metallic propellant tank structures. The most prevalent propulsion technology was LOX/RP-1 liquid cryogenic propulsion, followed by LOX/LH2 and solid rocket boosters. The relatively high number of product lines developing and using these technologies is an indication of commercial interest, as well as potential commercial benefit from the technology, and provides increased confidence that commercial industry will develop the needed technology.

Table 1.1.4: Technology Areas Being Developed by Multiple Product Lines

| Level 3 Tech Areas | Number of Products |
|--|--------------------|
| 3.2.1, 3.2.2, 6.1.2, 6.2.1 | 10 |
| 3.2.3, 3.2.4 | 9 |
| 2.1.1 | 8 |
| 2.3.1 | 7 |
| 1.1.1 | 6 |
| 6.1.1 | 5 |
| 1.1.2, 1.3.3, 2.2.3, 2.4.1, 3.1.1, 3.1.2, 6.3.1, 9.2.3, 10.2.3 | 4 |

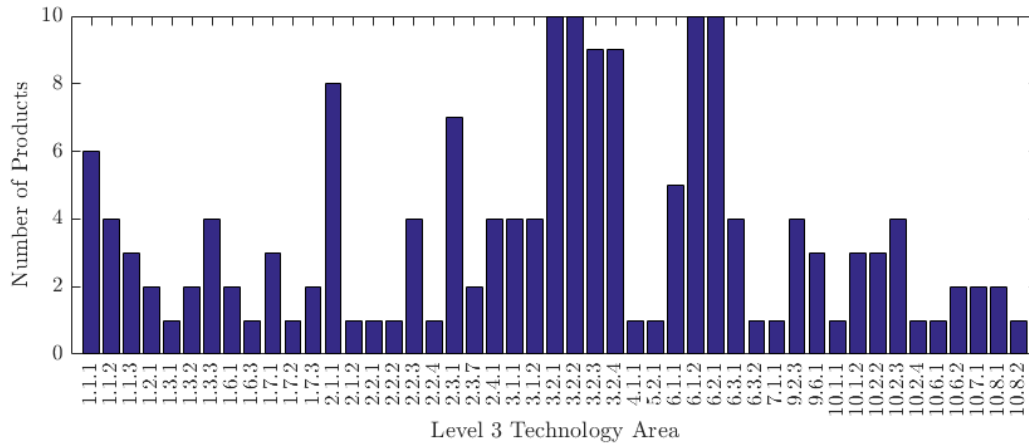


Fig. 1.1.11. Number of Products vs. Level 3 Technology Area. This figure provides a snapshot of the technology distribution in this sub-sector. This includes identifying the range of technology development across the sub-sector, as well as the focus areas of development in the sector.

Company Focus:

Next, the same technology distribution data can be looked at broken down by company (as seen in Fig. 1.1.12 below). This reveals which companies are specialized into particular technology areas and which are developing a wide range of technologies in this sector. Additionally, we can gain insights about whether certain technologies are being developed by a wide range of companies, which increases the commercial interest and potential for successful development. Additionally, we can identify the technologies with only one company developing it, which present an interesting case where one company sees a benefit in developing the technology but others do not, which leads to higher risk in the potential for successful development of that technology by commercial industry.

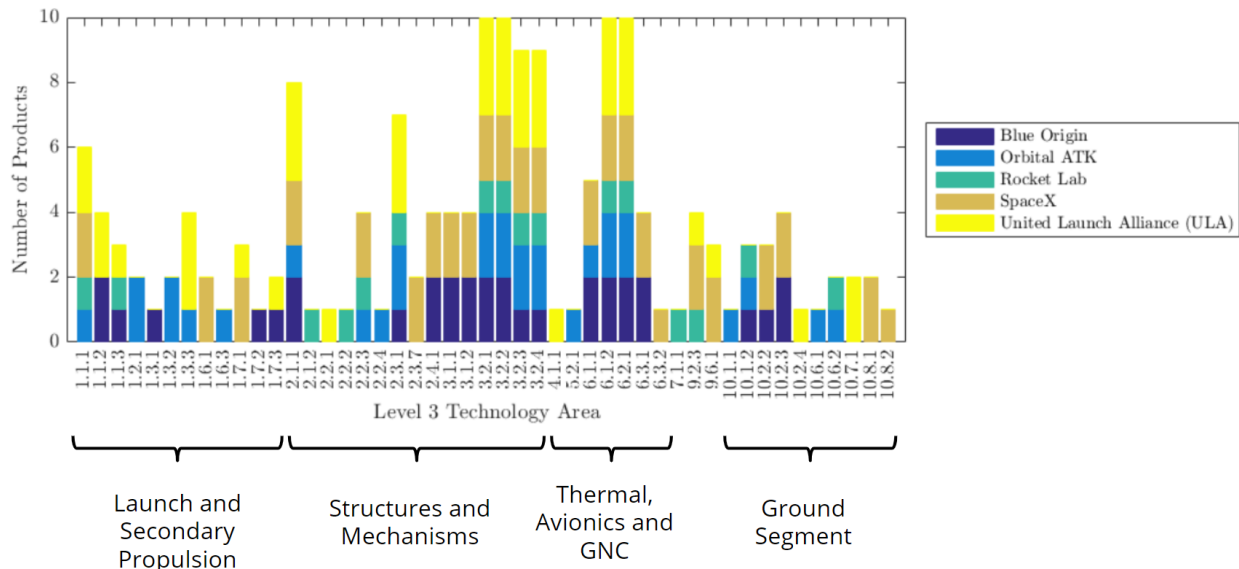


Fig. 1.1.12. Number of Products vs. Level 3 Technology Area broken down by company. This figure shows how technology distribution is broken down by company, and aids in identification of technologies being developed by multiple companies or just a single company, which has implications for the importance of that technology area to the sector as a whole and the confidence with which that technology will be developed by commercial industry.

The organizations that are most active across numerous technology areas with their product lines are reported in Table 1.1.5 below. Here we identify the major players in this sector, at least in terms of the number of technologies being developed, to be SpaceX, ULA, Blue Origin, and Orbital ATK. Rocket Lab is also very active in developing multiple technologies, but those technologies are used across only one product line.

Table 1.1.5: Organizations with the Highest Number of Technologies under Development

| Organization | Number of Technologies (repeated for multiple projects) | Number of Technologies (not repeated for multiple projects) |
|------------------------------|--|--|
| SpaceX | 46 | 24 |
| United Launch Alliance (ULA) | 41 | 20 |
| Blue Origin | 33 | 21 |
| Orbital ATK | 30 | 21 |
| Rocket Lab | 16 | 16 |

The technology areas with the most companies working on them are reported in Table 1.1.6 below. These technologies include separation systems, GNC sensors and actuators, metallic propellant tanks, LOX/RP-1 propulsion, LOX/LCH₄ propulsion, composite fairings, aerodynamic control surfaces, and private launch sites. All of these technologies, along with the push for reusable launchers, align well with, but are not explicitly mandated by, NASA's desire to facilitate a burgeoning commercial launch services sub-sector with reduced launch costs. The fact that these technology development efforts are driven by not only NASA's orbital launch needs, but also the payload requirements of commercial customers, inspire confidence in the health of this sub-sector. The ubiquitous need for launch services among government and commercial spacecraft alike has enabled NASA's success in promoting development in a sub-sector in such a way that NASA does not become the sole customer, but instead opens up the additional revenue streams for companies given the technology developed to meet NASA needs. With a foundational product and technological base, companies are seen to begin exploring new technologies for strategic reasons, such as LOX/LCH₄ propulsion and large composite structures.

Table 1.1.6: Technology Areas under Development by the Highest Number of Companies

| Level 3 Tech Areas | Number of Organization |
|---|------------------------|
| 3.2.1, 3.2.2, 3.2.3, 3.2.4, 6.1.2, 6.2.1 | 5 |
| 1.1.1, 2.1.1, 2.3.1 | 4 |
| 1.1.3, 2.2.3, 6.1.1, 9.2.3, 10.1.2 | 3 |
| 1.1.2, 1.3.3, 1.7.1, 1.7.3, 2.4.1, 3.1.1, 3.1.2, 6.3.1, 9.6.1, 10.2.2, 10.2.3, 10.6.2 | 2 |

The technology areas with only one company working on them are shown in Table 1.1.7 below. The reason for these particular technologies only being pursued by one company can be varied. For one, it may be that other companies have not yet identified the value proposition that the one company has. Alternatively, it may be that the technology is only important for the particular launch vehicle architecture selected by the company. Or, it may be that the technology simply is not actually that important for improving launch vehicles. Lastly, since NASA has been seen to be a driver of what commercial industry chooses to pursue, it may be that NASA simply hasn't expressed enough interest

for these companies to take the risk to pursue the technology development for purely commercial reasons. Either way, it is critical to determine the reason why a technology is only being pursued by one company, especially if NASA is hoping to benefit from cost-sharing opportunities through commercial development of a technology. If this is not possible, NASA will likely have to engage in traditional contracting processes or develop the needed technology in-house.

Table 1.1.7: Technologies Being Developed by a Single Company

| Level 3 Tech Areas | Organization |
|---|------------------------|
| 1.2.1, 1.3.2, 1.6.3, 2.2.4, 5.2.1, 10.1.1, 10.6.1 | Orbital ATK |
| 1.3.1, 1.7.2 | Blue Origin |
| 1.6.1, 2.3.7, 6.3.2, 10.8.1, 10.8.2 | SpaceX |
| 2.1.2, 2.2.2, 7.1.1 | Rocket Lab |
| 2.2.1, 4.1.1, 10.2.4, 10.7.1 | United Launch Alliance |

Status Focus:

Another way to look at the data on the technology development distribution in the sector is to look at the data broken down by the current status of the project, which can be active (currently operating), in development (ground demonstration with no launch schedule), planned (a launch has been scheduled), or retired (the project was launched and is no longer operating or being further developed). For this Launch Services sector, no retired products were considered because the large number of past vehicles became unwieldy. In addition, launch vehicles do not, in general, belong to the development status because all launch vehicle development projects typically have a stated goal of an anticipated first launch date. This data is shown in Fig. 1.1.13 below.

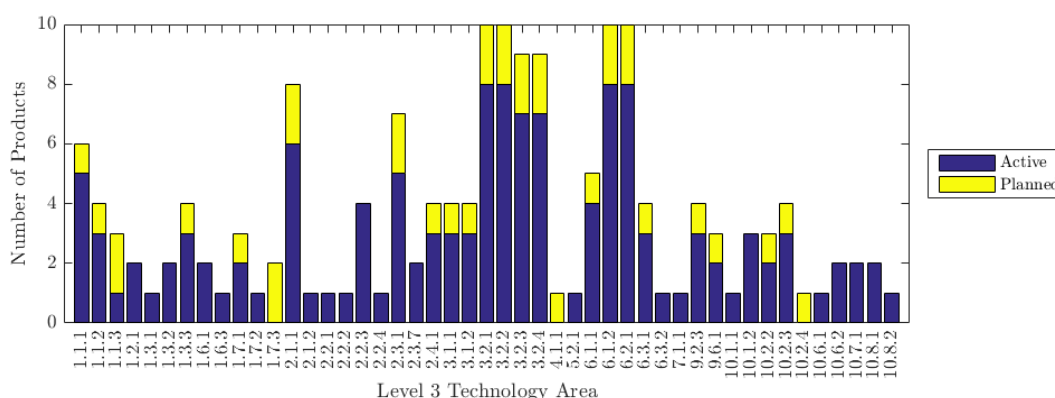


Fig. 1.1.13. Number of Products vs. Level 3 Technology Area broken down by project status. This figure shows how the technology development in the sector is distributed amongst various project statuses, including active and planned products. This allows for evaluation of the sector's current technology experience and the new technologies into which the sector is pushing with its future products.

Of all the technology-product pairs identified, the total status distribution is as follows: 131 active and 35 planned. The large number of active and planned statuses, identifies Launch Services as a strongly developed and growing sector. The sector rests on a long history of past launch vehicles and associated technology development projects, which are not captured here.

Technology areas with planned interest but no current active projects are interesting cases, and are presented in Table 1.1.8 below. These represent new directions for technology development in the sub-sector. These technologies may be higher risk development to achieve a competitive advantage in the sub-sector, may be a response to development of new supporting technologies, or may simply be a resurgence of previously retired technology. These technologies include air-captured reusable propulsion systems and cryogenic storage.

Table 1.1.8: Technology Areas Planned without Current Active Projects

| Level 3 Tech Areas | Number of Product Lines |
|--------------------|-------------------------|
| 1.7.3 | 2 |
| 4.1.1, 10.2.4 | 1 |

Technologies with associated products that all have the same status (see Table 1.1.9) present interesting cases for technology. If a technology is only active, that means it is currently used but has no future identified plans (which can just mean that the current product will continue operating) or past experience. There are numerous examples of this largely stemming from the fact that retired products were not considered as part of this analysis. If a technology is only active, the technology is being developed with no future identified plans.

Table 1.1.9: Technology Areas with a Single Status

| Level 3 Tech Areas | Status |
|---|---------|
| 1.2.1, 1.3.1, 1.3.2, 1.6.1, 1.6.3, 1.7.2, 2.1.2, 2.2.1, 2.2.2, 2.2.3, 2.2.4, 2.3.7, 5.2.1, 6.3.2, 7.1.1, 10.1.1, 10.1.2, 10.6.1, 10.6.2, 10.7.1, 10.8.1, 10.8.2 | Active |
| 1.7.3, 4.1.1, 10.2.4 | Planned |

Product Line Focus:

Next, the technology distribution data can be looked at broken down by product line (as seen in Fig. 1.1.14 below). Looking at the data in this way reveals what product lines are developing the most technologies, and which technologies are only being developed by a select few product lines, or by the most product lines. This can be an important assessment of the commercial interest in, and potential for development of, that particular technology.

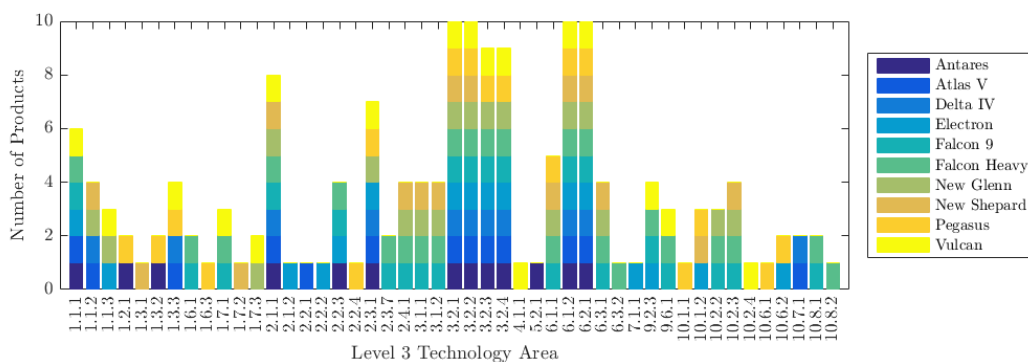


Fig. 1.1.14. Number of Products vs. Level 3 Technology Area broken down by product line.

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* In addition to these cited sources, information and data on each company’s activities was found on publicly available sources including company websites, space news articles, and government reports.

Sub-sector #4.1: In-Space Manufacturing Systems and Services

Sub-sector Overview

This emerging market subsector is comprised of systems and services that carry out fabrication, assembly, and integration activities beyond Earth's atmosphere [1]. All players in this sub-sector seek to take advantage of one or more relaxed design constraints enabled by moving manufacturing operations from the ground to the space environment. Currently, space systems are constrained by the fact that all components are built on Earth, launched aboard a rocket, and then operated in orbit for years with little to no opportunity for repair. Even though a spacecraft spends its entire operational life in orbit, some of the most stringent design constraints are driven by the short ride to orbit aboard a launch vehicle. However, when ISM is used, components are fabricated in the space environment in which they are intended to operate for their entire life. These components are no longer constrained by launch loads, fairing volume, or even gravity. In addition, ISM opens the possibility of acquiring feedstock via orbital material recycling or in-situ resource utilization (ISRU), in addition to the traditional launch of raw material from Earth. ISM systems can then leverage these relaxed design constraints to potentially lower the mass and cost of spacecraft and planetary surface systems with current capabilities or, perhaps more interestingly, provide improved performance and entirely new capabilities that are not currently possible [2].

Activities in the commercial in-space manufacturing (ISM) subsector can span from production of individual, low level components to entire systems and even spacecraft, habitats, or life support systems. ISM can be used for a wide variety of space applications, such as the production of large solar arrays, spare parts for ECLSS fluid systems, and exotic optical fiber for return to Earth, just to name a few. The needed capabilities for any of these ISM applications differ in terms of the required manufacturing methods, raw materials, and performance characteristics. Thus, the technology development in this sector, while largely focused on development or adaptation of manufacturing methods for the space environment, varies with each company's particular business plan. These business plans, in turn, depend on the demand for ISM services as driven by the current state of the art of other spacecraft systems, which are currently being launched.

Due to the perceived benefits, ISM has long been sought after, but commercially viable operations have remained elusive. Historical attempts at ISM have largely focused on the manufacture of extremely large space structures and the production of high-value products (that can only be made in the space environment) for return to Earth [3,4]. Recent efforts have continued to focus in these application areas, with the addition of interest in the manufacture of lightweight structures, on-demand spare parts, recycling systems, and construction using in-situ resources.

Sub-sector Interdependencies

This subsector is influenced by activities in the Launch Services sub-sector, particularly in terms of launch cost, which determines the cost of emplacing ISM capabilities in orbit and determines ISM business cases because it sets the cost for launched components for which ISM seeks to be an alternative. The ISM subsector is also influenced by the Space Resource Extraction sector because of the potential to acquire raw materials in-space for use as manufacturing feedstock.

This subsector exerts influence on the sub-sectors of Habitation Systems and Services, In-Space Transportation Systems and Services, On-Orbit Servicing, Extraction of Water and Volatiles, and Extraction of Metals, Minerals and Ores, as shown in Fig. 4.1.1 below. This influence is accomplished through ISM's ability to create components that have reduced cost and/or improved performance relative to the launched alternative. In addition, ISM opens the possibility for on-demand repairs and the use of in-situ resources for fabrication of useful components, which both reduce required launch mass.

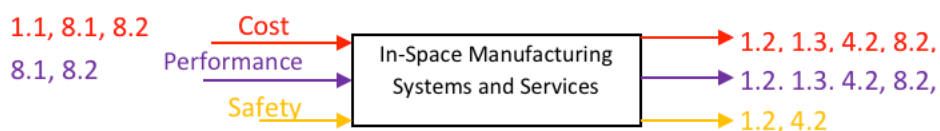


Fig. 4.1.1. Cost, Performance, and Safety Interdependencies of In-Space Manufacturing Systems and Services sub-sector with upstream and downstream sub-sectors.

Strategic Thrust and Figures of Merit

Following our survey of public information on organizations with a stake in ISM, the strategic thrust for this subsector is determined to be:

Fabricate a product with improved performance or reduced cost compared to existing Earth-fabricated products using manufacturing equipment with a rapid production rate, long life, and low size, weight, and power (SWaP).

This strategic thrust can be broken down into sub-thrusts and associated figures of merit as shown in Table 4.1.1 below. These figures of merit can be used to indicate the current state of the sector, as well as the potential of a particular development project and the impact of a technology development on high-level goals of the subsector.

It is useful to utilize these figures of merit to assess the current state of the art, which necessarily varies across the ISM industry due to the wide variety of potential application areas and needed manufacturing processes and raw materials. Figures of merit for mass, power, and production rate of existing ISM facilities are reported in Fig. 4.1.2 and Fig. 4.1.3 below. For any given product line, some of the figures of merit above, such as volume, mass, power, and production rate, can be readily gleaned if the project is well-documented with publicly available product specifications. However, public statements of a company's SWaP targets for a given system are often limited. Ref. [5] provides a listing of key ISM projects and their application area, as well as limited specifications.

Table 4.1.1: Strategic Sub-Thrusts and Associated Figures of Merit

| Strategic Sub-Thrusts | Figure of Merit |
|--|--|
| Reduced cost compared to launched alternative at isoperformance | ISM facility cost (\$) |
| | Cost savings relative to launch (\$) |
| Improved performance compared to launched alternative at isocost | Increase in product sale price relative to Earth-manufactured (\$) |
| | Mass savings relative to launch case (kg) |
| Manufacturing Equipment SWaP | Volume (m ³) |
| | Mass (kg) |
| | Power (W) |
| Responsive fabrication | Production rate (kg/yr) |
| | Customer lead time (mins) |
| Long life | Operational life (yr) |

Determining performance improvements relative to the launched alternative can be accomplished as long as the underlying ISM system specifications and operational plans are known. However, cost information is difficult to gather because it is typically only kept internally in competitive industry. This makes determination of cost savings relative to the launched alternative challenging because the true costs are not typically known. One approach to address this challenge is to analyze concepts in terms of their maximum allowable facility cost such that the concept proves commercially viable (i.e. cheaper than the launched alternative) at the desired total production breakeven point. This analysis approach, as detailed in [5], allows for identification of key technology development and cost reduction targets for commercially viable ISM across a wide range of potential application areas. Another approach which assists with cost evaluations and which does not rely on dollar costs is the Lifetime Embodied Energy (LEE) cost metric and methodology, which estimates an objective lifetime cost for alternative systems in units of embodied joules of a common-denominator energy source for all relevant inputs. Since all human activities require energy, it is possible to measure the cost of any system or product in terms of the LEE of all direct and indirect inputs it requires. This total lifetime cost can be converted to specific, per-unit costs using principles analogous to those employed in financial and managerial accounting for the proper treatment of investments and durables. For in space manufacturing, a LEE cost analysis exercise can be accomplished by computing and allocating the embodied energy contributions of launch, energy, materials, and labor for the ISM product architecture compared to the conventional launch of Earth-manufactured components [6].

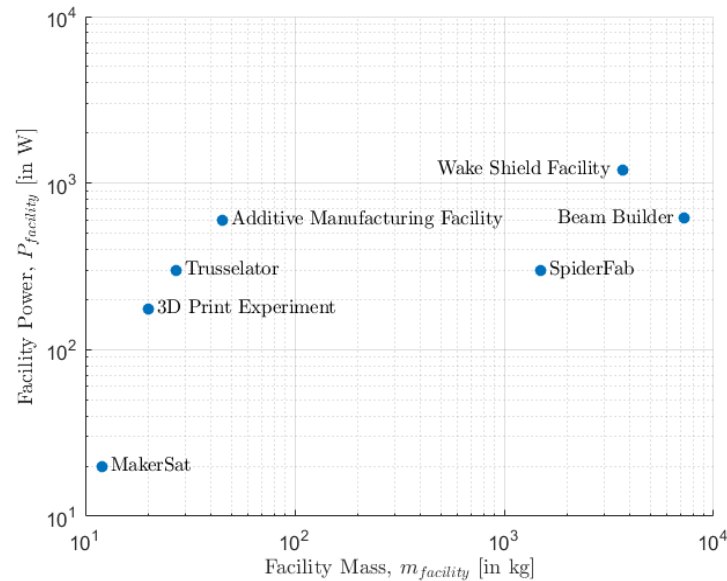


Fig. 4.1.2. ISM facility power vs. facility mass shows a trend of increasing power with increasing facility mass across a wide range of ISM facilities, each designed for a different application. The power and mass are seen to vary by up to three orders of magnitude, which shows how different ISM concepts can be depending on the desired application. Additionally, the power is seen to plateau with increasing mass beyond a point, likely because additional power is not necessary, or is too difficult to provide to the system in orbit. Manufacturing methods that require lower average power are preferred when possible.

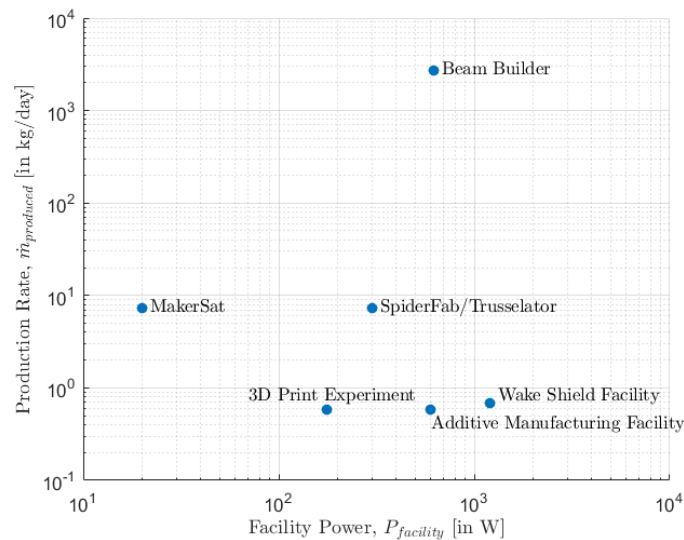


Fig. 4.1.3. ISM facility production rate vs. facility power. Interestingly, power and production rate do not show a clear correlation. In principle, one would expect a particular manufacturing process to require a certain amount of energy to fabricate a product. Thus, increasing power would be expected to result in increased production rate. However, this is only true for a particular manufacturing process and product, whereas different concepts in the ISM sector have very different processes, products, and required production rates. Most ISM concepts have low production rates on the order of 1 kg/day, but this be almost four orders of magnitude larger, as for the Beam Builder concept.

Patent Application Activity

A patent analysis, the results of which are summarized in Fig. 4.1.4. below, shows that this sector is relatively small and nascent. Some patent application activity was seen in the early 1980's with a recent surge in activity after 2011. This recent surge in activity corresponds with a recent increase in NASA SBIR funding for ISM projects (see "Government Investment" section below). A wide range of companies are conducting activities in this sector, which is dominated by US companies, such as Made in Space and Tethers Unlimited. Recent work has been focused on working of plastics, additive manufacturing, metal-working and casting, as well as optics, crystal growth, and medical applications.

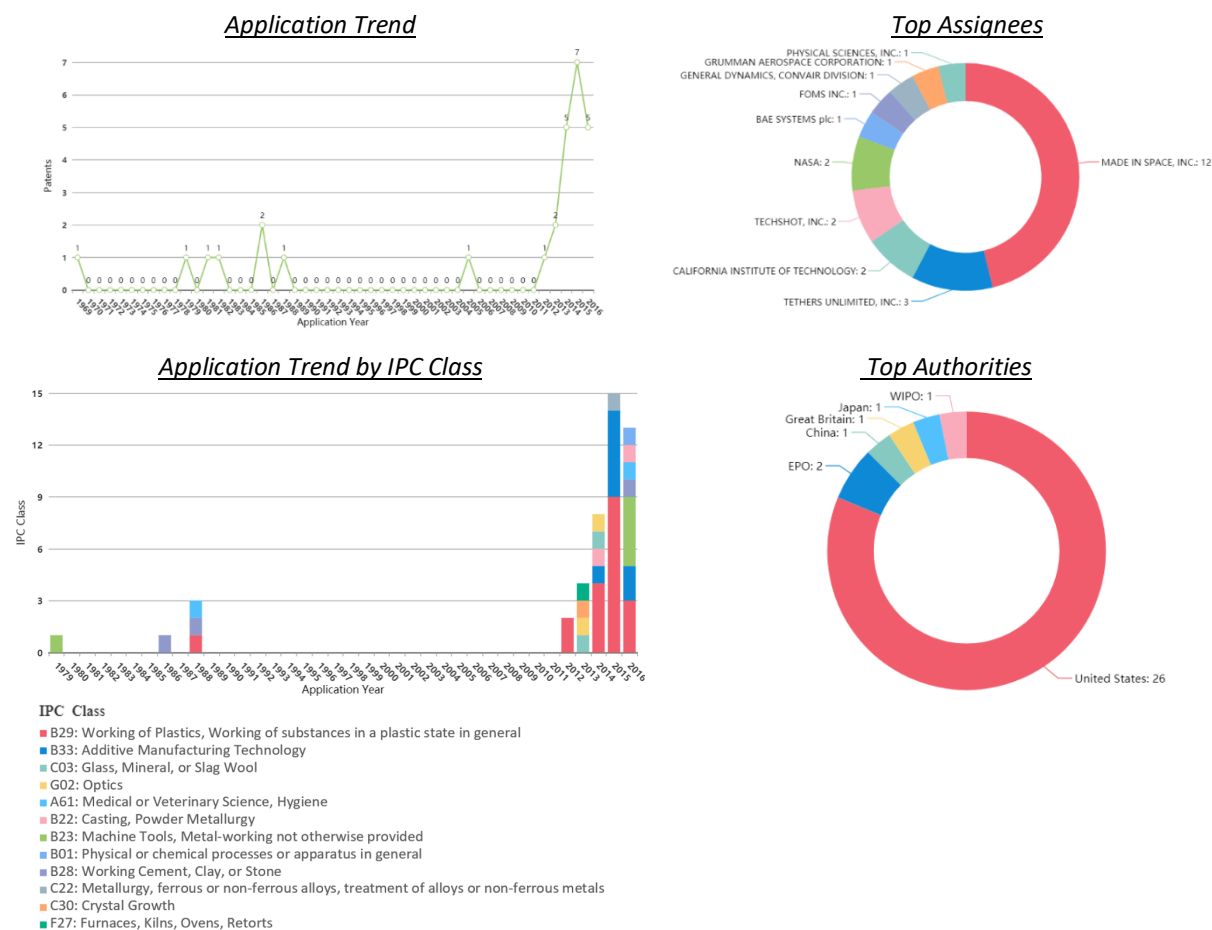


Fig. 4.1.4. Patent Application Trends in In-Space Manufacturing

Government Investment

Government investment into the development of ISM technologies by commercial industry has been provided through a variety of forms, such as Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), Tipping Point Solicitations, and the Next Space Technologies for Exploration Partnerships (NextSTEP) program. Across these funding programs, government has made efforts to push the sub-sector beyond the tipping point of commercial viability, and strong correlation between patent applications and government funding is seen. It is recommended that focus should be placed on the development of dual-use technology, with benefits to both NASA and industry, to improve potential of continued commercial activity after the completion of government funding.

SBIRs and STTRs

Perhaps most interestingly for this industry is the fact that government investment via SBIRs has shown a dramatic increase since 2012 (see Fig. 4.1.5) [7]. Prior historical investment in ISM was mostly provided to industry from 1985 to 1992, with limited and sporadic investment throughout the late 1990's and early 2000's. The recently renewed commercial investment has led to, and will continue to lead to, commercial ISM technology advancements as seen by recent and planned ISM ground development projects and flight missions, as well as a recent trend in increasing ISM-related patent applications (see "Patent Activity" section above). This renewed funding is well aligned with other pressures creating a suitable environment for ISM, such as the advent of new manufacturing methods suitable for ISM, like additive manufacturing, and falling launch costs, which enable more activity in space and enables large structures and return-to-Earth products, as well as the push for human deep space exploration, which requires a new spares logistics paradigm that can be enabled by ISM.

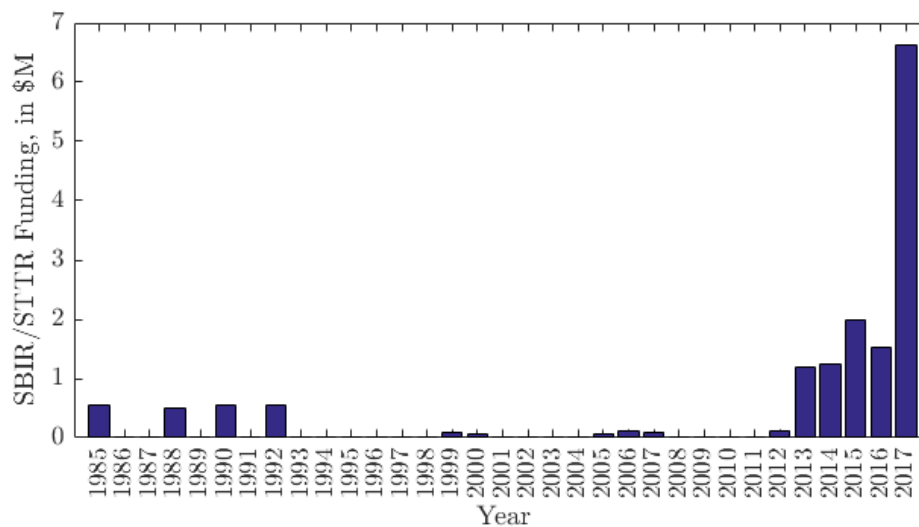


Fig. 4.1.5. NASA and DARPA funding to commercial industry via SBIRs and STTRs from 1985 to 2017, relatively modest early investments, sporadic and minimal funding from 1993 to 2011, and a recent increasing surge in funding.

The composition of companies receiving government SBIR/STTR funding has changed in recent history, as shown in Fig. 4.1.6. A total of \$15.3 million in funding has been given to 14 different companies over 33 years through Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR) from both NASA and DARPA. Tethers Unlimited has received the most funding of \$8.15M for 14 different projects. Made in Space has received \$1.84M over 8 different projects. While Physical Sciences has received \$1.65M for 7 different projects, each of these projects were carried out from 1985 to 2000, with no recent activity. Techshot has received \$1.12M in total for 4 different projects. The rest of the companies have received less than \$1M each for at most 3 projects each. Fig. 4.1.6 shows government funding in millions of dollars, while Fig. 4.1.7 shows the number of projects sponsored by government funding.

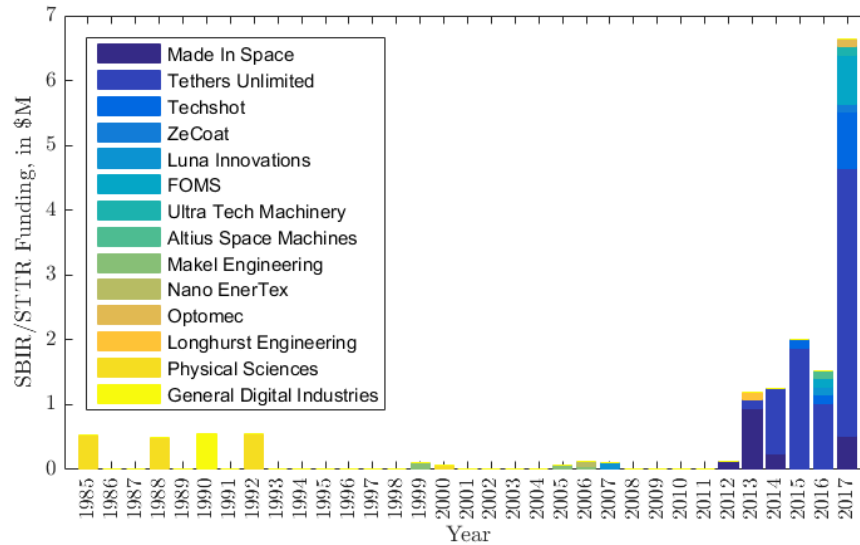


Fig. 4.1.6. Amount of NASA and DARPA money funding commercial industry via SBIRs and STTRs from 1985 to 2017 broken down by company receiving investment. The companies receiving investment are seen to change over time, with the four companies that received investment from 1985 to 2006 no longer receiving investment. A new set of ten companies have emerged to capture the high recent government investment in ISM. These companies, from 2007 onward, have received \$12.8M. Despite the large number of companies involved, \$12M of this recent total funding has gone to the following four companies: Tethers Unlimited, Made In Space, Techshot, and FOMS.

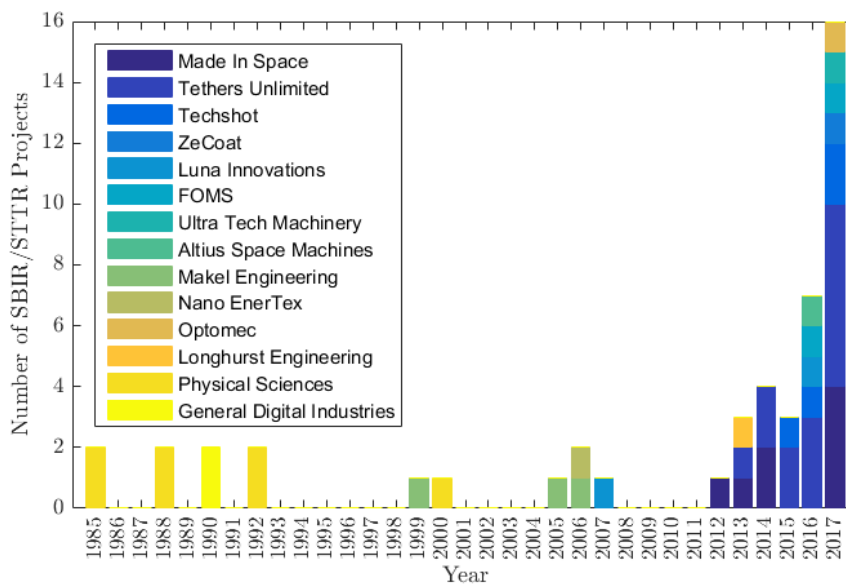


Fig. 4.1.7. Number of NASA and DARPA awarded projects to commercial industry via SBIRs and STTRs from 1985 to 2017 broken down by company receiving investment. By looking at the data in this way, we can see that the SBIRs and STTRs are more evenly distributed in terms of number of projects awarded than they are in terms of total monetary value awarded. However, the same big players of Tethers Unlimited, Made In Space, and Techshot are still identified. Physical Sciences also received a large number of projects but has not been recently active. FOMS has only received two project awards, but has received the fifth highest amount of total funding since 1985.

The large number of companies receiving awards is promising for creative new technology development, and is likely a result of this being a nascent industry. Key players have emerged in this sector and are receiving a large portion of government investment, and thus have already provided, and are expected to provide, the largest fraction of technology advancements. Companies that have received a large number of awards are signaled as having persistent interest in the development of ISM technologies. However, a limited number of projects with a high monetary value of award could be an indication of specialized interests in ISM and may still result in measurable technology development results. In addition, flight test projects typically require much more funding than ground prototyping efforts.

Tipping Point Solicitation

NASA has funded ISM through the “Utilizing Public-Private Partnerships to Advance Tipping Point Technologies” solicitation. This program has the goal of promoting technology development to the point where commercial industry can qualify them for market after the completion of the government funding period. The technologies for investment under this program were ones that would benefit commercial industry as well as align with NASA’s strategic plan. One subset of proposals under this solicitation was for technologies for robotic, in-space manufacturing and assembly of spacecraft and space structures. Under this tipping point solicitation, fixed-price, milestone-based contracts were awarded in 2015 in the range of \$1M to \$20M each over two years. Under this solicitation, there is the possibility for continued funding for a potential flight demonstration and infusion into future exploration missions. Recipients of this award were Made In Space Archinaut, Orbital ATK (now NGIS) Commercial Infrastructure for Robotic Assembly and Servicing (CIRAS), and Space Systems Loral (SSL) Dragonfly.

NextSTEP Program

NASA’s Next Space Technologies for Exploration Partnerships (NextSTEP) program has the goal of creating prototypes of space-based, on-demand fabrication capabilities. Funding totaling \$10.2M over an 18 month period has been awarded to Interlog Corporation, Techshot, and Tethers Unlimited. These projects, beginning in December 2017, are aimed at developing and demonstrating ground-based prototypes of a multi-material fabrication lab.

Summary

Government funding of ISM activity has provided resources and opportunities needed by a burgeoning industry reaching the tipping point of commercial potential. However, it is important to note that in these efforts, NASA will inherently encourage commercial projects that align with NASA’s mission needs, while other commercial endeavors will likely be left unfunded. Finding a way for promotion of dual-use technologies (ones that benefit both NASA and industry) will allow commercially viable ISM operations to be achieved, which would not require continued government investment to be sustainable.

Selected Companies and Associated Product Lines

Companies that are key players in the ISM sector were identified based on known funded projects, publications, and websites indicating interest in the field. The listing of these selected companies and their product lines is reported in Table 4.1.2 below, along with the status of the project and the year it was first discussed publicly by the company. This is the list of the companies and product lines that were used to evaluate the technology development being pursued by commercial industry in this sector.

Table 4.1.2: Selected Companies and Associated Product Lines

| Selected Companies | Product Line (Year Introduced) |
|--|--|
| ACME Advanced Materials | Active: <ul style="list-style-type: none"> - Silicon Carbide Wafer Microgravity Processing |
| Altius Space Machines, Inc. | Development: <ul style="list-style-type: none"> - ISP3: In-Situ Printing Plastic Production System for Space Additive Manufacturing (2016) |
| Convair | Retired: <ul style="list-style-type: none"> - SCAFEDS: Space Construction Automated Fabrication Experiment Definition Study (1981) |
| FOMS, Inc. | Development: <ul style="list-style-type: none"> - SPACEFORM: Space Facility for Orbital Remote Manufacturing (2016) |
| Longhurst Engineering, PLC | Development: <ul style="list-style-type: none"> - In-Space Friction Stir Welding Machine (2013) |
| Luna Innovations, Inc. | Development: <ul style="list-style-type: none"> - In-Situ Generation of Polymer Concrete Construction Materials (2016) |
| Made in Space | Retired: <ul style="list-style-type: none"> - 3D Print Experiment (2014) Active: <ul style="list-style-type: none"> - Additive Manufacturing Facility (2016) - Optical Fiber Production in Microgravity Experiment (2017) Development: <ul style="list-style-type: none"> - Satellite Manufacturing Machine (2011) - R3DO: Plastic Recycling System (2014) - Archinaut (2016) - Industrial Crystallization Facility (2017) - Vulcan Advanced Hybrid Manufacturing System (2017) - External Augmentation of Generic Launch Elements (2017) |
| NASA Marshall with Lehigh University and U.S. National Bureau of Standards | Retired: <ul style="list-style-type: none"> - MLR: Monodisperse Latex Reactor (1982) |
| Northrop Grumman | Retired: <ul style="list-style-type: none"> - Beam Builder (1981) Development: <ul style="list-style-type: none"> - CIRAS: Commercial Infrastructure for Robotic Assembly and Services (2015) - Space Recycler (2018) |
| Optomec, Inc. | Development: <ul style="list-style-type: none"> - Adaptive Laser Sintering System for In-Space Printed Electronics |
| Space Systems Loral | Development: <ul style="list-style-type: none"> - Dragonfly (2015) |

| Selected Companies | Product Line (Year Introduced) |
|-----------------------------|---|
| Space Vacuum Epitaxy Center | Retired: <ul style="list-style-type: none"> - Wake Shield Facility (1994) |
| TechShot, Inc. | Planned: <ul style="list-style-type: none"> - BioFabrication Facility (2018) Development: <ul style="list-style-type: none"> - SIMPLE: Sintered Inductive Metal Printer with Laser Exposure (2016) - STEPS: Software and Tools for Electronic Printing in Space (2017) - Space Plastic Recycling System (2015) |
| Tethers Unlimited, Inc. | Planned: <ul style="list-style-type: none"> - Refabricator: Positrusion Filament Recycling System (2018) Development: <ul style="list-style-type: none"> - SpiderFab (2012) - Trusselator (2013) - CRISSP: Customizable, Recyclable ISS Packaging (2015) - MakerSat (2016) - Constructable GEO Platform (2016) - ERASMUS: Food Contact Safe Plastics Recycler (2016) - MAMBA: Metal Advanced Manufacturing Bot-Assisted Assembly (2017) - AXON: The Automated X-Link for Orbital Networking Connector (2017) - OrbWeaver (2017) |
| Ultra Tech Machinery, Inc. | Development: <ul style="list-style-type: none"> - ISS Multi-Material Fabrication Laboratory using Ultrasonic Additive Manufacturing (2017) |
| ZeCoat Corp. | Development: <ul style="list-style-type: none"> - Battery-Powered Process for Coating Telescope Mirrors in Space (2017) |

Associated NASA Projects

According to the 2015 NASA Space Technology Roadmaps, ISM is an enabling technology that is needed for the following NASA design reference missions: DRM 8 Crewed to Mars Moons, DRM 8a Crewed Mars Orbital, and DRM 9 Crewed Mars Surface Mission (DRA 5.0). The technology need date is identified as 2021, 2027, and 2027, respectively.

Other ISM-related NASA projects include microgravity materials science and manufacturing research on Skylab, Space Shuttle, and ISS. In addition, JPL has investigated printable spacecraft and DARPA carried out the Phoenix project. Although NASA was influential in promoting the Grumman Beam Builder and Convair SCAFEDs projects, in-space assembly, not fabrication or welding, was selected for construction of ISS. Nevertheless, there were existing concepts for the construction of large trusses built out of the Space Shuttle payload bay, as well as concepts for welded space station assembly. Recently, NASA's still expresses an interest in the fabrication of large space structures and in microgravity materials science research. However, the primary importance of ISM for exploration missions has been identified as the on-demand production of spare parts to reduce logistics mass and reduce risk.

Key Technology Distribution

Throughout this section, technology numbers refer to those in the "Commercially Active Technology Area Breakdown Structure" section at the end of this report.

After identifying the key technologies associated with each product line for each company, the following analysis of results was conducted to identify trends in technology development interest across the subsector.

Sector Focus:

First, we can look at which technologies are actively developed in this sector and how prevalent each technology is across the range of product lines in this sector. As seen in Fig. 4.1.8 below, technology development in this sector is spread across the following technology areas: TA 2: Structures, TA 4: Thermal Control, TA 6: GNC and ADCS, TA 9: Manufacturing, TA 13: ECLSS, and TA 14: Robotics and Autonomy. The most prevalent technology, as shown in Table 4.1.3 below, is additive manufacturing of plastics. The next most prevalent technologies are additive manufacturing of composites, recycling of plastics, and robotic arms. The high number of product lines developing and using these technologies is an indication of commercial interest, as well as potential commercial benefit from the technology, and provides increased confidence that commercial industry will develop the needed technology.

Table 4.1.3: Technology Areas Being Developed by Multiple Product Lines

| Level 3 Tech Areas | Number of Products |
|---|--------------------|
| 9.3.1 | 7 |
| 9.3.6, 9.5.1, 12.1.1 | 5 |
| 2.2.5, 2.3.3, 2.3.4, 9.3.2, 9.3.3, 11.1.2, 12.2.3 | 4 |
| 9.3.5, 9.5.2, 9.7.2, 11.1.1 | 3 |

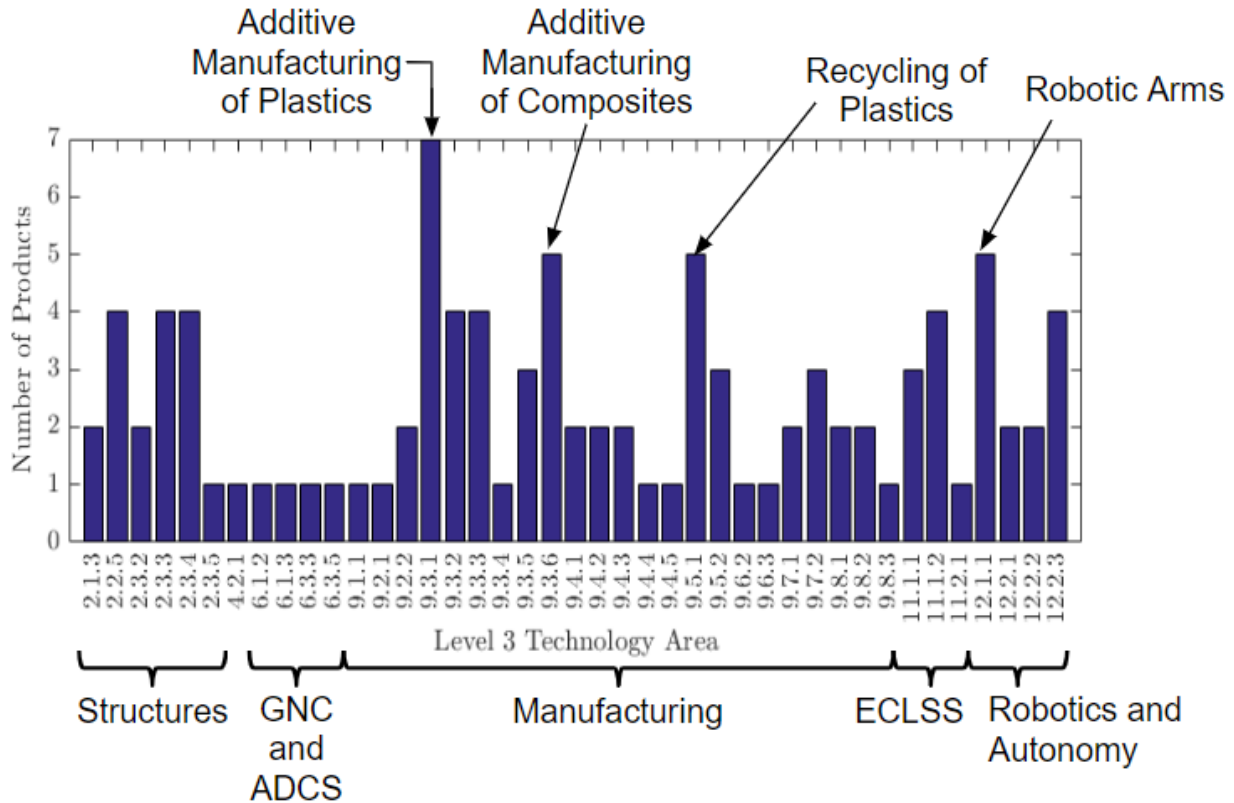


Fig. 4.1.8. Number of Products vs. Level 3 Technology Area. This figure provides a snapshot of the technology distribution in this sub-sector. This includes identifying the range of technology development across the sub-sector, as well as the focus areas of development in the sector.

Company Focus:

Next, the same technology distribution data can be looked at broken down by company (as seen in Fig. 4.1.9 below). This reveals which companies are specialized into particular technology areas and which are developing a wide range of technologies in this sector. Additionally, we can gain insights about whether certain technologies are being developed by a wide range of companies, which increases the commercial interest and potential for successful development. Additionally, we can identify the technologies with only one company developing it, which present an interesting case where one company sees a benefit in developing the technology but others do not, which leads to higher risk in the potential for successful development of that technology by commercial industry.

The organizations that are most active across numerous technology areas with their product lines are reported in Table 4.1.4 below. Here we again identify the usual major players in this sector, and find that Made In Space and Tethers Unlimited truly dominate the industry in terms of the number of technologies being developed. However, the other top companies are still very active in developing multiple technologies.

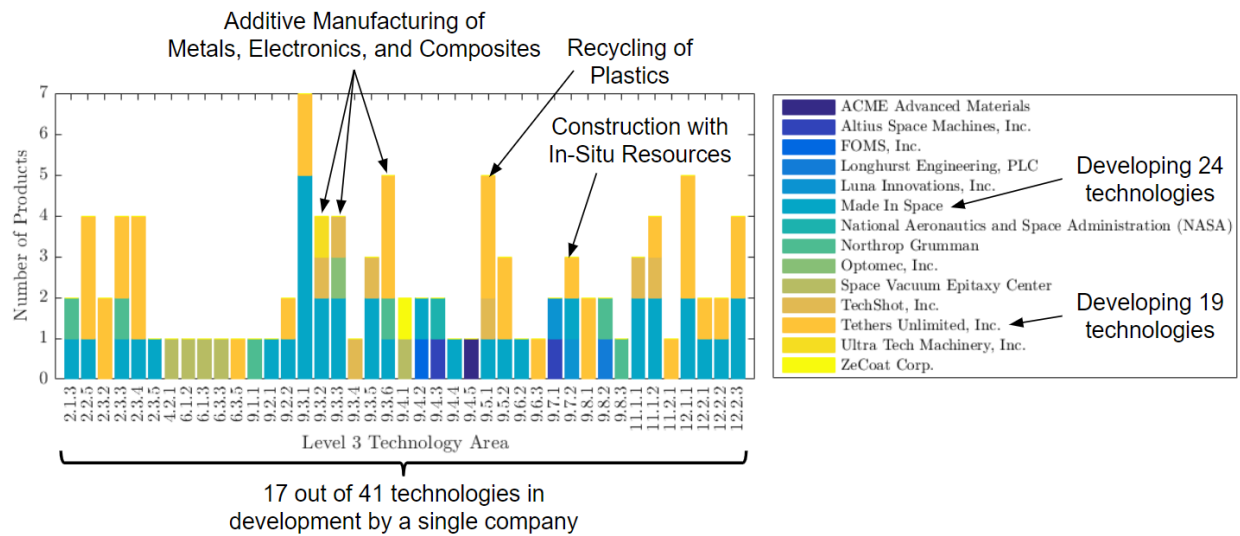


Fig. 4.1.9. Number of Products vs. Level 3 Technology Area broken down by company. This figure shows how technology distribution is broken down by company, and aids in identification of technologies being developed by multiple companies or just a single company, which has implications for the importance of that technology area to the sector as a whole and the confidence with which that technology will be developed by commercial industry.

Table 4.1.4: Organizations with the Highest Number of Technologies under Development

| Organization | Number of Technologies (repeated for multiple projects) | Number of Technologies (not repeated for multiple projects) |
|-----------------------------|--|--|
| Made In Space | 35 | 24 |
| Tethers Unlimited, Inc. | 35 | 19 |
| TechShot, Inc. | 7 | 7 |
| Northrop Grumman | 6 | 6 |
| Space Vacuum Epitaxy Center | 5 | 5 |

The technology areas with the most companies working on them are reported in Table 4.1.5 below. These technologies include additive manufacturing of metals, electronics, and composites, as well as the recycling of plastics and construction with in-situ resources. All of these technologies align well with interests that NASA has been pushing for application of ISM on future deep space exploration missions. However, this does not mean that these technologies are the ones that provide good business cases for ISM outside of the potential for future NASA contracts for deep space exploration missions. Nevertheless, these technologies could be transferable to operations on a commercial space station and on future deep space exploration missions NASA could potentially pay the operator of an ISM spare parts capability on a per use basis, while scientists and others could also pay for the capability to produce new experiments based on findings during the mission, as one example.

Table 4.1.5: Technology Areas under Development by the Highest Number of Companies

| Level 3 Tech Areas | Number of Organizations |
|--|-------------------------|
| 2.3.3, 9.3.2, 9.3.3, 9.3.6, 9.5.1, 9.7.2, 11.1.2 | 3 |
| 2.1.3, 2.2.5, 2.3.4, 9.2.2, 9.3.1, 9.3.5, 9.4.1, 9.4.2, 9.4.3, 9.5.2, 9.7.1, 9.8.2, 11.1.1, 12.1.1, 12.2.1, 12.2.2, 12.2.3 | 2 |

The technology areas with only one company working on them are shown in Table 4.1.6 below. The reason for these particular technologies only being pursued by one company can be varied. For one, it may be that other companies have not yet identified the value proposition that the one company has. Alternatively, it may be that the technology is only needed based on the particular ISM design solution that the company has selected. Or, it may be that the technology actually is not that crucial for commercial ISM operations. Lastly, since NASA has been seen to be a driver of what commercial industry chooses to pursue, it may be that NASA simply hasn't expressed enough interest for these companies to take the risk to pursue the technology development for purely commercial reasons. Either way, it is critical to determine the reason why a technology is only being pursued by one company, especially if NASA is hoping to benefit from cost-sharing opportunities through commercial development of a technology. If this is not possible, NASA will likely have to engage in traditional contracting processes or develop the needed technology in-house.

Table 4.1.6: Technologies Being Developed by a Single Company

| Level 3 Tech Areas | Organizations |
|------------------------------------|-----------------------------|
| 2.3.2, 6.3.5, 9.6.3, 9.8.1, 11.2.1 | Tethers Unlimited, Inc. |
| 2.3.5, 9.2.1, 9.4.4, 9.6.2 | Made In Space |
| 4.2.1, 6.1.2, 6.1.3, 6.3.3 | Space Vacuum Epitaxy Center |
| 9.1.1, 9.8.3 | Northrop Grumman |
| 9.3.4 | TechShot, Inc. |
| 9.4.5 | ACME Advanced Materials |

Status Focus:

Another way to look at the data on the technology development distribution in the sector is to look at the data broken down by the current status of the project, which can be active (currently operating), in development (ground demonstration with no launch schedule), planned (a launch has been scheduled), or retired (the project was launched and is no longer operating or being further developed). This data is shown in Fig. 4.1.10 below.

Of all the technology-product pairs identified, the total status distribution is as follows: 5 active, 78 in development, 3 planned, and 13 retired. The large number of development status, compared to active and retired identifies ISM as a nascent sector. In addition, the limited number of active statuses and planned statuses, means that most development is for ground demonstrations without firm launch plans. This can be interpreted as concerning for the industry's future, or just an indication that the industry is not ready for many flight programs and that those launch plans will come in due time as the needed technology reaches an appropriate level of maturity.

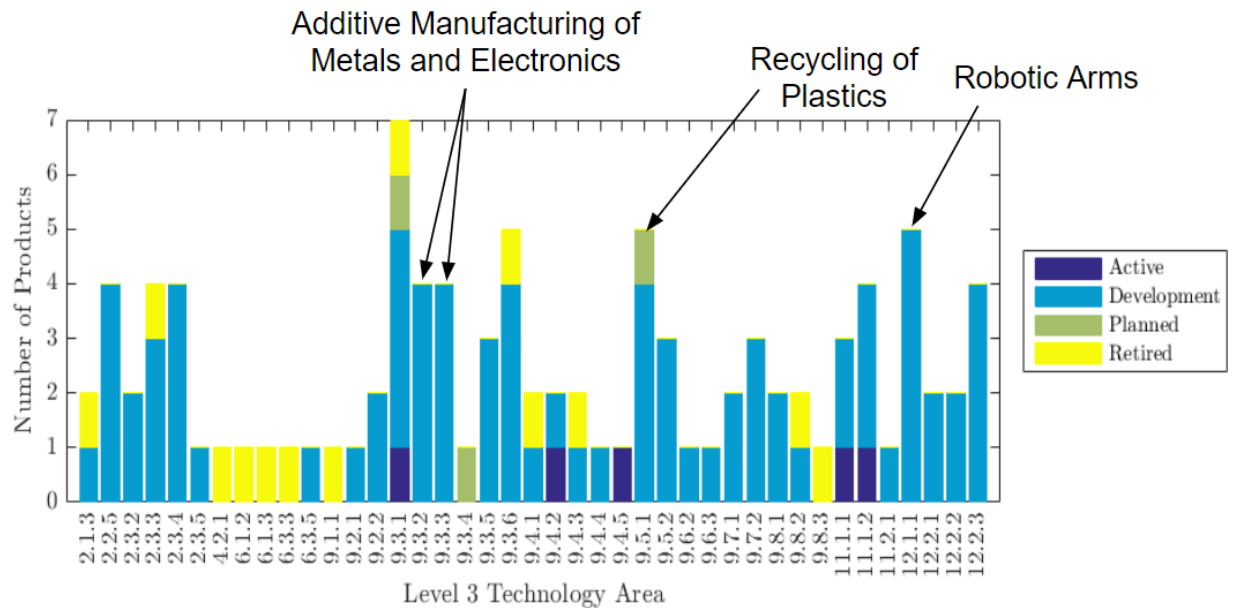


Fig. 4.1.10. Number of Products vs. Level 3 Technology Area broken down by project status. This figure shows how the technology development in the sector is distributed amongst various project statuses, including active, development, planned, or retired products. This allows for evaluation of the sectors past technology experience and the new technologies into which the sector is pushing with its future products.

Technology areas with significant current interest and no prior retired projects or existing active projects are interesting cases, and are presented in Table 4.1.7 below. The most prevalent of these technologies is plastics recycling, and robotic arms, as well as metal additive manufacturing, electronics additive manufacturing, assembly end effectors, and structures optimized for additive manufacturing ISM.

Table 4.1.7: Technology Areas without Prior Retired or Active Projects

| Level 3 Tech Areas | Number of Product Lines |
|---|-------------------------|
| 9.3.6, 9.5.1, 12.1.1 | 5 |
| 2.2.5, 2.3.3, 2.3.4, 9.3.2, 9.3.3, 12.2.3 | 4 |
| 9.3.5, 9.5.2, 9.7.2 | 3 |

Technologies with associated products that all have the same status (see Table 4.1.8) present interesting cases for technology. If a technology is only active, that means it is currently used but has no future identified plans (which can just mean that the current product will continue operating) or past experience. One example of this is semiconductor wafer healing by ACME Advanced Materials. If a technology is only active, the technology is being developed with no future identified plans. And if the technology is only retired, then the technology is no longer relevant or needed for future activities in the industry, and, so, it will not be developed by commercial industry alone. Some of this retired technologies include furnaces, forming of metals, and in-space riveting.

Table 4.1.8: Technology Areas with a Single Status

| Level 3 Tech Areas | Status |
|---|-------------|
| 9.4.5 | Active |
| 2.2.5, 2.3.2, 2.3.4, 2.3.5, 6.3.5, 9.2.1, 9.2.2, 9.3.2, 9.3.3, 9.3.5, 9.4.4, 9.5.2, 9.6.2, 9.6.3, 9.7.1, 9.7.2, 9.8.1, 11.2.1, 12.1.1, 12.2.1, 12.2.2, 12.2.3 | Development |
| 9.3.4 | Planned |
| 4.2.1, 6.1.2, 6.1.3, 6.3.3, 9.1.1, 9.8.3 | Retired |

Product Line Focus:

Next, the technology distribution data can be looked at broken down by product line (as seen in Fig. 4.1.11 below). Looking at the data in this way reveals what product lines are developing the most technologies, and which technologies are only being developed by a select few product lines, or by the most product lines. This can be an important assessment of the commercial interest in, and potential for development of, that particular technology.

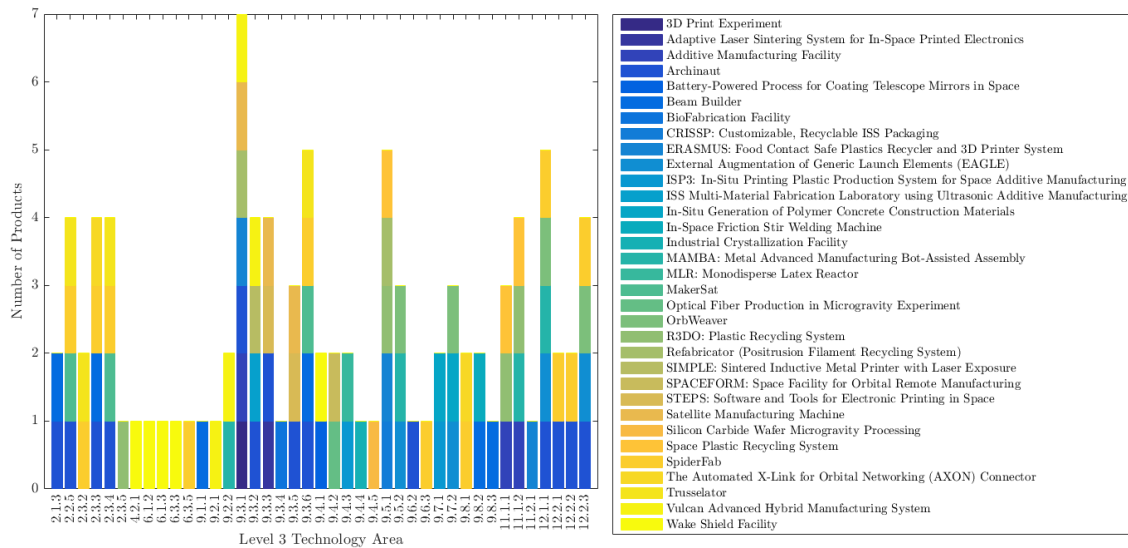


Fig. 4.1.11. Number of Products vs. Level 3 Technology Area broken down by product line.

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* In addition to these cited sources, information and data on each company's activities was found on publicly available sources including company websites, space news articles, and government reports.

Sub-sector #6.1: Global Positioning System (GPS)

Sub-sector Overview

This market sector comprises the commercial provision or use of positioning, navigation, and timing (PNT) information via GPS for terrestrial or space-based assets. Capabilities employed by this sector include precision positioning, tracking, and timing information. For the purpose of this report, the sector is divided into those responsible for the provision of GPS (namely, the US government), and downstream manufacturers of GPS receivers and subsystems, with a focus on the latter. Customers that make use of GPS equipment may include a wide variety of users in sectors such as transportation, aviation, shipping, location based services (LBS), survey or mapping services, and spacecraft manufacturers and owners. The focus of this sub-sector analysis is the ways in which GPS technology enables in-space activities.

History of GPS Services

The provision of GPS is overseen by the US government, with the system first becoming fully operational in 1993. Comprised of a space, ground and control segment, two signals are provided, one for civilian use, and one for military use. The civilian signal is provided free-of-charge to the international community, and through a series of initiatives by the US government, has been made to be more reliable and responsive to civilian and commercial users worldwide. Initially, GPS data was made public through the National Oceanic and Atmospheric Administration (NOAA), which catalyzed growth and development of the first commercial surveying market. This growth and the Federal Aviation Administration's (FAA) initiative to publish performance standards for receiver technology led to crucial initial commercial investment in GPS R&D [1].

Since those initial investments in GPS R&D, GPS equipment has undergone miniaturization and reduction in cost, leading to a ubiquity in reliance on GPS technology to replace other navigation methods. As shown in Fig. 6.1.1 and 6.1.2, as the cost of GPS receiver technology has dramatically decreased, sales of receivers have increased. The current commercial value of navigation and positioning services in the US is about \$55.7 billion/year, about 0.3% of the GDP with end-use applications in sectors such as transportation, aviation, shipping, location based services (LBS), and survey or mapping services [2]. the cost of disruption to the system has been estimated to be \$96 billion per year in the United States, the equivalent of 0.7% of the US economy [2].

Over the past ten years, GPS receivers have been increasingly used for in-space navigation systems, and NASA has identified at least 80 planned or launched missions that utilize GPS technology. Carrier phase measurements, used by GPS, offer low measurement noise when compared to other pseudorange techniques and real-time relative navigation at the (sub-) centimeter level using single frequency GPS receivers has been reliably demonstrated [4].

Average Cost of GPS Receivers Over Time

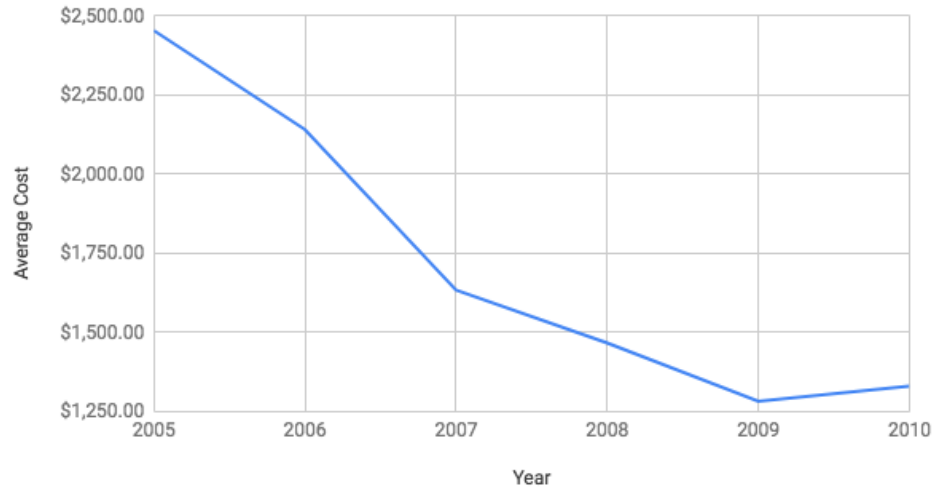


Fig. 6.1.1. Since 2005, the average cost of GPS receivers have fallen drastically, mirrored by a steady increase in sales of GPS receivers shown in the following figure.

Average Sales (millions) over Time

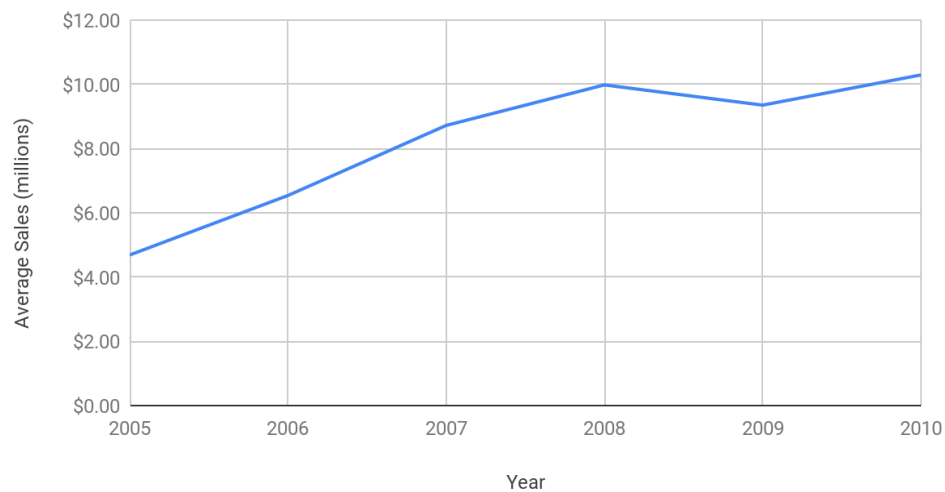


Fig. 6.1.2 A steady rise in average sales of GPS receivers follows a similar drop in price, shown in the previous figure.

In the space industry, navigation and positioning services provide position, velocity, and timing information onboard, which leads to increased autonomy. Orbit information derived from navigation and positioning services includes attitude control, geocoding of payload data, autonomous instrument and spacecraft operations, formation flying and rendezvous, and orbit control. Commercial GPS subsystem developers have tapped into this sector, moving towards producing space-qualified technologies with demonstrated flight heritage. However, additional features are required for spaceborne receivers due to the high doppler shift and high altitude of flight [5].

Sub-Sector Interdependencies

Table 6.1.1 below reports the sub-sectors that impact the cost, performance, and risk/safety of the GPS sub-sector. Similarly, the impact of the GPS sub-sector on other sectors in terms of cost, performance, and risk/safety is reported in Table 6.1.2 below. End-users of GPS technology, especially in the Space Economy, are reliant upon the provision of GPS and benefit from the reduction of cost and size of GPS sensors and systems. GPS will play a crucial role in enabling sectors reliant on in-space maneuvers such as orbital docking and rendezvous, in-space manufacturing, and asteroid tracking and mining.

Table 6.1.1: Sub-sectors that influence the GPS sector in terms of Cost, Performance and Risk

| Cost | Performance | Risk/Safety |
|--|---|--|
| <ul style="list-style-type: none"> -Launch Services -Subsystem Manufacturing -Spacecraft Integration -Spacecraft Assembly -Spacecraft Testing | <ul style="list-style-type: none"> -In-Space Transportation -Subsystem Design -Data Processing, Storage, and Dissemination -Fixed Satellite Services -Satellite Operations | <ul style="list-style-type: none"> -Orbital Debris Tracking and Removal |

Table 6.1.2: Sub-sectors that are influenced by the GPS sector in terms of Cost, Performance and Risk

| Cost | Performance | Risk/Safety |
|--|--|---|
| <ul style="list-style-type: none"> -In-Space Transportation -Spacecraft Assembly | <ul style="list-style-type: none"> -Fixed Satellite Services -Satellite Operations -Orbital Debris Tracking and Removal | <ul style="list-style-type: none"> -In-Space Transportation -Satellite Operations |

Strategic Thrust and Figures of Merit

Following the survey of activity in this subsector, the strategic thrust identified for the GPS sub-sector is to:

Provide increasingly precise, up-to-date, and reliable information about the position of objects on Earth and in space in a cost-effective and efficient manner.

This central thrust can be decomposed into sub-thrusts. The progress of the sector in addressing these sub-thrusts can in turn be captured by certain Figures of Merit (FOM). The sub-thrusts and FOM's are described in Table 6.1.2 below.

Table 6.1.2. Listing of strategic sub-thrusts broken down into quantitative Figures of Merit

| Strategic Sub-Thrusts | Figure of Merit |
|------------------------|---------------------------------------|
| Accurate | Time (ns) |
| | Position (m) |
| | Velocity (cm/sec) |
| Redundant and Reliable | Signals Available (L1, L2, L5) |
| | Number of Channels |
| | Anti-jamming/anti-spoofing Capability |
| | Cold Start Time (minutes) |
| Cost Effective | Mass (kg) |
| | Volume (cm ³) |
| | Power Consumption (W) |

For use on-board spacecraft, GPS subsystems must be increasingly efficient in terms of volume occupied, mass, and power consumption. In order to be low-cost and compact, producers may take advantage of more commercial-off-the-shelf (COTS) technology, as has been the recent trend. Additionally, ensuring GPS reliability is crucial as glitches in GPS can lead to serious mission failures. For example, in September 2018, Exos Aerospace's first launch of their SARGE rocket was prevented from reaching its final altitude due to a failure in the GPS receiver [6]. To this end, there may be a trend towards adopting more hybrid receivers which will use GPS and one or more other GNSS system as well as additional channels and more correlators per channel in order to enhance sensitivity and mitigate multipath effects.

Patent Application Activity

A patent search regarding GPS technologies was conducted using Google Patent Search. In order to limit patents to applications of GPS technologies in spacecraft, the search was limited to patents classified under CPC B64G (Cosmonautics; vehicles or equipment therefor). The following terms were mentioned most frequently in patent titles, indicating some applications of GPS technology in spacecraft: orbit (48), control (38), vehicle (26), navigation (24), attitude (19), position (16), autonomous (16), debris (15), communication (15), orbital (13), and constellation (11). Figure 6.1.3 depicts patents filed and granted over time. Overall, this patent analysis indicates the sustained interest and activity in using GPS in navigation and positioning applications for spacecraft.

GPS Patents (CPC: B64G)

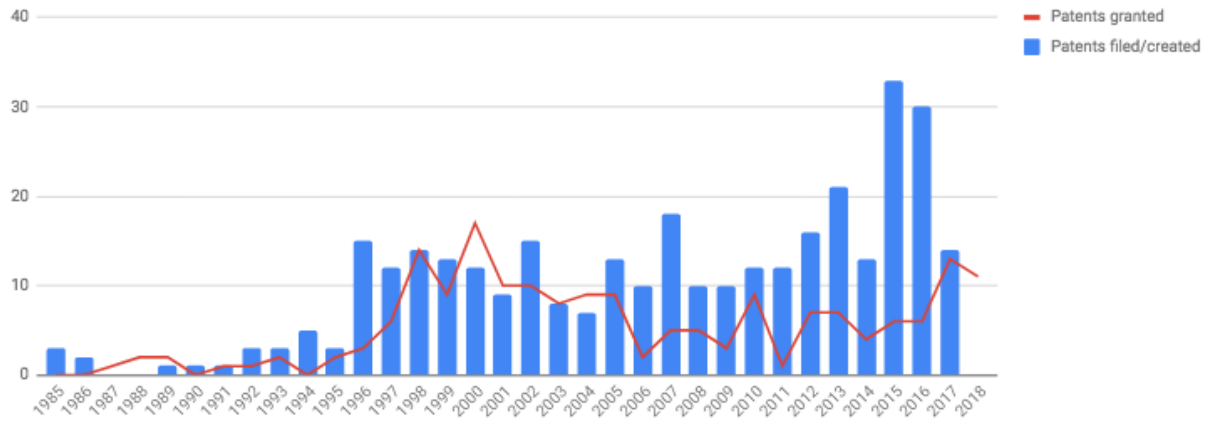


Fig. 6.1.3. Patent applications and patents granted over time.

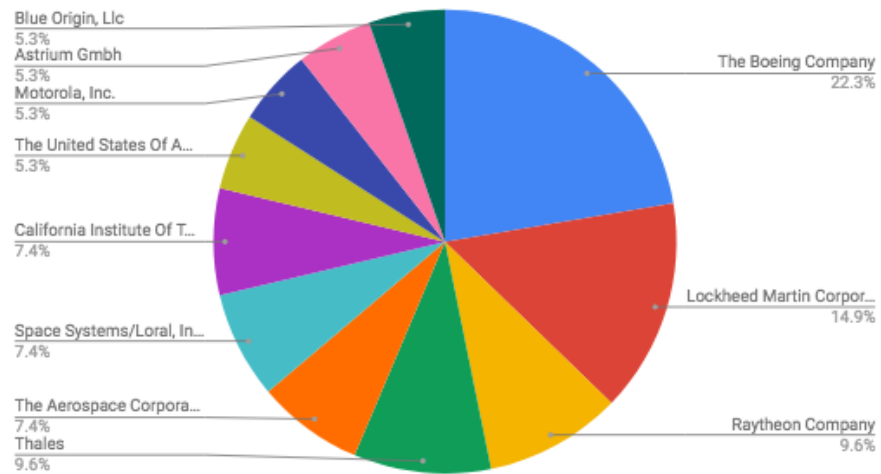


Fig. 6.1.4. Breakdown of top companies granted patents in spacecraft GPS technologies.

Government Investment

Government investment into the development of GPS technology by commercial industry (see Fig. 6.1.5) has been provided through a variety of forms, including Small business Innovation Research (SBIR), Small Business Technology Transfer (STTR). Early government investment and NASA research into use of GPS technology for spacecraft has clear applications in commercial industry. For example, the development of the Navigator GPS Receiver, designed by the NASA Goddard Space Flight Center, enabled the use of GPS navigation in high Earth orbit (HEO), geostationary orbit (GEO), and other high altitude applications or weak-signal area applications. Thus far, via the NASA Technology Transfer Program, the technology has been licensed to Moog Broad Reach and Space Vector Corp.

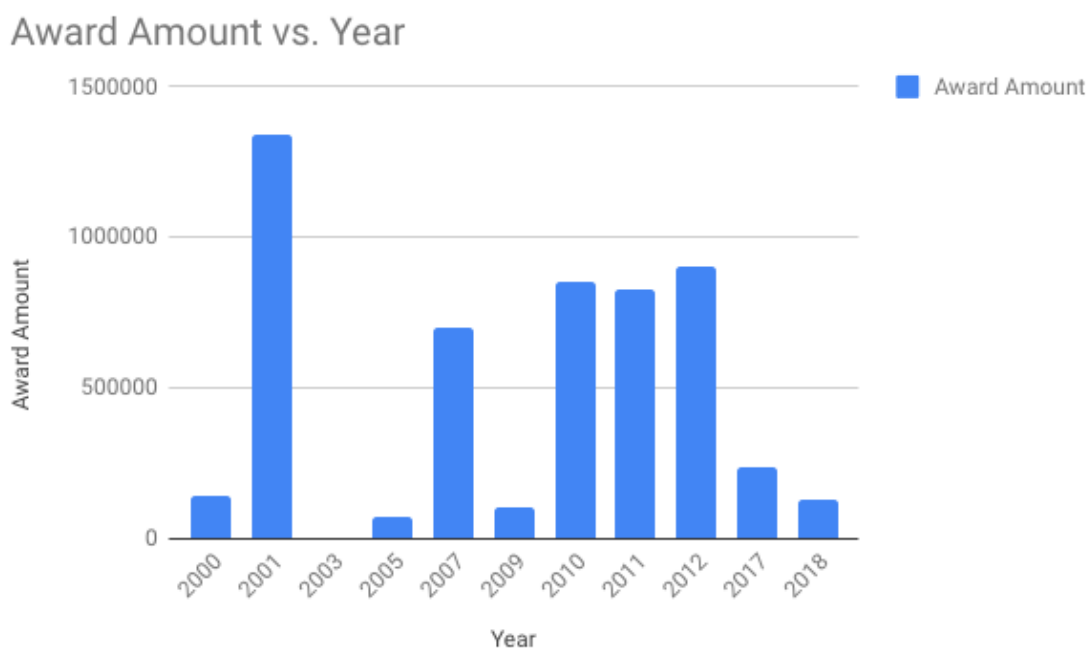


Fig. 6.1.5 NASA funding to commercial industry via SBIRs and STTRs. With overall sustained funding, there is an early surge in 2001, closer to when GPS became fully operational in 1996.

Selected Companies and Associated Product Lines

The satellite navigation industry consists of companies that provide the satellite technology (the upstream sector), as well as companies that exploit the technologies (the downstream sector). Since GPS is a publicly available signal, we focus on downstream applications of navigation and positioning such as producers of sensors and receivers. Furthermore, since this report is concerned with enabling the commercial space sector, the focus here is on GPS technologies used for in-space services and customers. The technologies and capabilities proposed by these companies are discussed in a subsequent section. A selected list of GNSS providers and their products is given in Table 6.1.3.

Table 6.1.3: Selected GNSS Companies and Associated Products

| Company (Founded) | Key Products |
|--------------------------|--|
| General Dynamics | Sentinel M-Code GPS Receiver Viceroy GPS Receiver |
| BAE Systems | SpaceNav GPS Receiver for Space Applications |
| Moog | TriG RO (proposed) NavSBR |
| BRE | Pyxis Nautica |
| Pumpkin Space Systems | GPS Receiver Module (GPSRM 1) Kit |
| SpaceQuest | GPS-601 Satellite GNSS Receiver |

Associated NASA Projects

NASA has relied on partnerships with commercial space to develop, launch, and operate the satellites used for GPS provision. The 24 satellites in the current constellation were manufactured by Boeing and Lockheed Martin and were launched using vehicles provided by United Launch Alliance and Lockheed Martin. The initial control segment was developed by General Dynamics in 1974 and a contract was granted to IBM in 1980 to develop the operational control system (OCS). Since then, Boeing and Lockheed Martin have been identified as the prime contractor and subcontractor for the control segment while Raytheon was charged with developing the “Next Generation Operational Control System” in 2010. As GPS undergoes modernization with the launch of Block III satellites, NASA continues to rely on commercial partnerships [4].

Comparison of GPS with other International Global Navigation Satellite System (GNSS)

Since GPS became fully operational, other countries have developed their own satellite navigation systems. The provision of these signals often enhance the capability and reliability of GNSS receivers, especially as more receivers develop capabilities for multi-GNSS signal reception. A comparison of international GNSS is given below:

Table 6.1.4: Comparison of GPS with other International Global Navigation Satellite Systems

| Parameter | GPS | GLONASS | Galileo | BeiDou Navigation Satellite System |
|------------------------------|----------------|--------------------------|--------------------------|------------------------------------|
| First Launch | 1978 | 1982 | 2005 | 2000 |
| Full Operational Capability | 1996 | 1996-2011 | 2012-2013 | |
| Funding | public | public | public & private | |
| Nominal number of SV | 24 | 24 | 27 | 23 |
| Orbital Planes | 6 | 3 | 3 | 3 |
| Orbital inclination (deg) | 55 | 64.8 | 56 | 55 |
| Semi-major axis (km) | 26,560 | 25,508 | 29,601 | |
| Orbit plane separation (deg) | 60 | 120 | 120 | |
| Revolution period (h.min) | 11.57 | 11.15 | 14.4 | |
| Geodetic reference system | WGS-84 | PE-90 | GTRF | CGCS2000 |
| Signal separation | CDMA | FDMA | CDMA | |
| Number of frequencies | 3 (L1, L2, L5) | one per two antipodal SV | 4 (E1, E6, E5, E5a, E5b) | 2 (B1I, B2I) |
| Frequency (MHz) | L1: 1,575.420 | G1: 1,602.000 | E1: 1,575.420 | B1I: 1,561.098 |
| | L2: 1,227.600 | G2: 1,246.000 | E6: 1,278.750 | B2I: 1,207.140 |
| | L3: 1,176.450 | G3: 1,204.704 | E5: 1,191.795 | |
| Number of ranging codes | 11 | 6 | 10 | |
| Accuracy | < 5m | 4.5-7.4m | 0.01-1m | 0.1-10 m |

Technologies

The table below lists the technologies which were found to be of particular importance to the satisfaction of the strategic thrust and sub-thrusts of the GPS sub-sector. They are extracted from the commercially active technology breakdown structure developed for this research.

Table 6.1.5: Key Technologies for the GPS sub-sector

| Level 1 Technology Area | Level 2 Technology Area | Level 3 Technologies |
|------------------------------------|------------------------------------|--|
| 5. Avionics | 5.1 On-Board Computing | 5.1.1 High Volume Data Storage (Gigabits to Terabits) |
| | 5.2 Systems | 5.2.2 Radiation Hardened Electronics |
| 6. GNC and ADCS | 6.1 Actuators | 6.1.1 Aerodynamic Control Surfaces 6.1.2 Reaction Control 6.1.3 Attitude control |
| | 6.2 Sensors | 6.2.1 Inertial Measurement 6.2.2 Fine Attitude Sensors 6.2.3 Timekeeping and time distribution 6.2.4 Relative and Proximity/Differential Navigation |
| | 6.3 Software | 6.3.1 Landing Control Laws 6.3.2 Simultaneous Multi-Booster GNC Laws 6.3.3 Ram-facing control 6.3.4 Maintaining microgravity orbit free of perturbations 6.3.5 Rendezvous and Proximity Operations 6.3.6 Rapid ADC Solutions (for Targeting, Slewing and Pointing) 6.3.7 Virtual Relative Position Services 6.3.8 Auto Precision Formation Flying |
| 10. Ground Segment | 10.3 Data Pipeline | 10.3.1 High Capacity Data Archiving |

Key Technology Distribution

Throughout this section, technology numbers refer to those in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report.

For use in commercial spacecraft, GPS technologies have the following applications and advantages:

Timekeeping and Time Distribution: GPS receivers can serve as on-board low-cost alternatives to other timekeeping methods currently used such as spacecraft atomic clocks. The push here is to provide integrated, space-qualified systems with ultra-high time accuracy and frequency stability.

Onboard Auto Navigation and Maneuver: GPS receivers can be used for ranging as well as trajectory, orbit and attitude determination, thus serving as an alternative to ground-based telemetry and tracking systems, allowing for autonomous onboard navigation. Existing space-qualified GPS units provide similar services to ground-based systems at lower-cost with increased availability, improved safety margins at space launch facilities, more responsive and precise position and velocity data and less delays. There is also potential for GPS receivers to be used for attitude determination by using differential signals from multiple on-board antennas, however this may be limited to LEO applications. Critical for improving capabilities and reducing support requirements for many future space missions, these subsystems need to reduce dependence on routine position fixes from the Earth, freeing the communication network for other tasks.

Relative and Proximity Navigation: GPS can enable multi-platform relative navigation (such as determining relative position, velocity, attitude, or pose) which can improve interoperability between space platform operations. The use of carrier phase differential GPS has been proven to be a reliable source of relative navigation in LEO. In cases of constellation control, GPS can provide a single point-of-contact to control for the orbit maintenance of large numbers of space vehicles. Further enhancement of positioning capability could be achieved through the ability to augment signals from terrestrial pseudolites (transmitting GPS ‘look-alike’ signals).

Auto Precision Formation Flying: With greater integration of GPS with other sensor technologies and wireless communications, formation flying can be done with minimal intervention from ground crews. Along with developments in Hybrid and Autonomous Positioning Systems (HAPS), navigation and timing systems will become more independent, relying less on external updates. Virtual platforms can provide automatic “station-keeping” and relative position services for advanced science tracking maneuvers such as interferometry. Additionally, GPS can replace or augment tracking radars with higher precision, lower-cost GPS units for range safety and autonomous flight termination.

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* In addition to these cited sources, information and data on each company's activities was found on publicly available sources including company websites, space news articles, and government reports.

Sub-sector #7.1: Earth Imaging/Sensing

Sub-Sector Overview

This market sector comprises commercial activities which obtain, process and provide data on terrestrial objects, phenomena and scenes as gathered by sensing technologies onboard space-based assets. Capabilities employed by this sector include passive and active imaging across many spectral bands, meeting required coverage areas and revisit times, and delivery of data of varying temporal, spectral, spatial, and radiometric resolution. Customers of this sector may include commercial entities in fields such as agriculture and land development, business intelligence, scientific communities, humanitarian organizations and government, military and national security agencies, etc.

Past and Present of Commercial Remote Sensing

One of the principle fronts of the Space Race between the United States and the Soviet Union during the latter half of the 20th century was the building of greater and greater capabilities to covertly surveil adversaries' activities and territory. Thus the beginning of space-based remote sensing is largely attributed to military and national security developments of the 1950's and 60's. Private activity in the sector during this time comprised of subsystem development contracts for these Top-Secret military and intelligence programs. For example, in 1958 the Itek Corporation was contracted to develop the camera system for the CIA imaging satellite program, CORONA [1]. This pattern of private involvement in government-run remote sensing programs should not yet be considered commercial. The contracts were highly prescribed, the spacecraft were owned and operated by the government, and the products were strictly secret preventing their commercialization.

In later decades, truly commercial ventures began in the field of space-based remote-sensing. A new pattern emerged of satellite imaging systems owned and operated by private entities. Still, primary customers remained military and government entities. For example, during the Gulf War of the early 1990's, the American coalition purchased satellite imagery from the French commercially operated Spot satellites. Again during the Iraq and Afghanistan conflicts in the years after 9/11, the Department of Defense (DoD) contracted two commercial satellite imaging companies to provide high-resolution imagery [2]. In these two examples however, the very same imagery was commercially available to other entities such as postwar relief organizations, scientific communities and domestic/global policy centers.

This paradigm has led to the US government, and specifically the DoD, being highly dependent on commercial satellite imagery. In a 2004 report, Wong found that the US was the largest customer of remote sensing images making up over 25% of company revenues [3]. As of 2017, the government remains a large customer as exemplified by an active National Geospatial-Intelligence Agency (NGA) contract with imagery provider DigitalGlobe worth at least \$300 million [2]. Since 2004 however, the customer base for commercial remote sensing products has expanded beyond military/government customers to include agriculture and land development, scientific communities, infrastructure planning and development, humanitarian and relief organizations, and countless other businesses.

Vedda finds that “commercial remote sensing has moved into the social and economic mainstream as internet mapping sites and smartphone apps featuring satellite imagery have become common tools” [4]. In many cases, companies do not see themselves as satellite imagery providers, but rather as data companies capable of generating unique knowledge and insights from their highly specialized capabilities. The most successful players in the market leverage constellations of satellites capable of acquiring images across the electromagnetic spectrum, large stores of archived imagery, and advanced algorithms to deliver analytical products to their customers. This has led to significant growth in the sector. In 2017, the global commercial remote sensing industry was valued at \$1.8 billion; in 2018, this number has risen by more than 20% to \$2.2 billion as measured by Bryce and the Satellite Industry Association [2,5]. Established and new companies alike are proposing bold technologies and capabilities to further capitalize on this success.

Sub-Sector Interdependencies

The Earth sensing sub-sector is an important player within the larger Space Economy. It is both a significant customer of products and services provided by other sectors and a developer of technologies and capabilities critical to other sectors. These interdependencies can be captured as flows amongst the sectors; they can be categorized in the context of the three primary systems concerns of Cost, Performance, and Risk/Safety. Thus, in Fig. 7.1.1 below, the sub-sectors of the Space Economy whose products and services impact the Cost, Performance and Risk/Safety of an Earth Sensing mission are shown as inputs while those sectors impacted by the Earth Sensing sub-sector are shown as outputs. These impacts can be direct, such as the purchasing of launch services, or indirect, such as the advances/developments in data processing within the Earth Sensing sub-sector which may be leveraged by the wider Data Processing, Storage and Dissemination sub-sector.

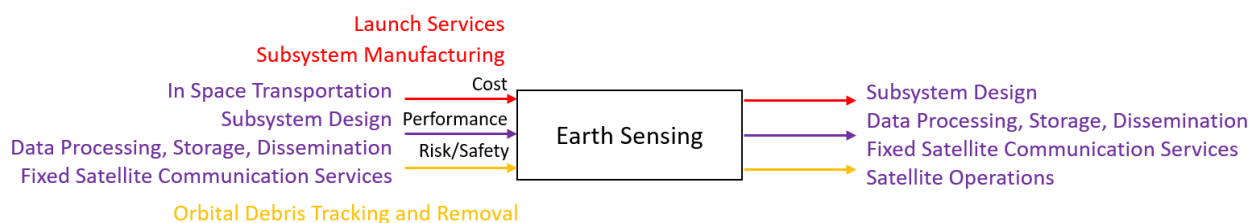


Fig. 7.1.1. Earth Sensing Sub-Sector Flows including Cost, Performance, and Risk/Safety

As shown in Fig. 7.1.1, the Earth Sensing sub-sector is an end customer of several products and services provided by other sectors of the Space Economy including launch vehicles, in-space transportation (namely propulsion systems), and dependent on the degree of custom-built vs. off-the-shelf components, satellite subsystem design and manufacturing. For these two, as well as for data processing and fixed satellite communications, many Earth Sensing operators will employ their own systems, algorithms, architectures and ground stations. As such, while not a customer of these sectors, the Earth Sensing sector still impacts these other sectors through development of similar technologies – in a larger interdependency flow depiction, this relationship might manifest itself as flow loops amongst sectors.

The Earth Sensing sector is an outward facing sector within the larger Space Economy. Its primary customers – those purchasing imagery and other analysis products – typically lie outside of the bounds of the Space Economy. This is in contrast to the more inward-facing sectors such as Launch Services and On-Orbit Services whose customers are primarily organizations active in other space sectors. Like some of the telecommunications sub-sectors, Earth Sensing is one of the interface points between the Space Economy and the larger economy and thus a driver for a vibrant and responsive space industry.

Strategic Thrust and Figures of Merit

The commercial remote sensing sector seeks to leverage the unique capabilities of space-based imaging platforms to address a wide variety of customers. While diverse in their intended usage of satellite imagery, these customers have several similar fundamental needs which players in the sector are competing to address. These needs align with those commonly expected during today's Internet Age, namely responsiveness, speed, and accessibility. As such, the major strategic thrust of the commercial remote sensing sector can be described as:

To cost-effectively develop, deploy and operate space systems capable of delivering more frequent, higher resolution, larger coverage, more responsive geospatial data to a growing government, military and industry customer base.

This central thrust can be decomposed into sub-thrusts. The progress of the sector in addressing these sub-thrusts can in turn be captured by certain Figures of Merit (FOM). The sub-thrusts and FOM's are described in Table 7.1.1 below.

Table 7.1.1: Strategic Sub-Thrusts and Associated Figures of Merit

| Strategic Sub-Thrusts | Figure of Merit (units) |
|-----------------------|--|
| More Frequent | Revisit Time (days) |
| | Downlink Rate (Mbps) |
| | Archive Refresh Time (days) |
| Higher Resolution | Spatial Resolution (m) |
| | Spectral Resolution (# of bands, bandwidth, and color) |
| | Radiometric Resolution (bits) |
| Larger Coverage | Capacity (km ² /yr) |
| | On-board Storage (Gbits) |
| | Archived Data (Gbits) |
| More Responsive | Request to Image Delivery Time (days) |
| | Direct-ness of Link from Satellite to End User (degrees of sep.) |
| | Percentage of Useable Imagery (%) |
| | Ratio of Archived to Sold Data |
| Cost Effective | Asset Mass (kg) |
| | Fleet Development Cost (\$/asset) |
| | Fleet Launch Cost (\$/asset) |
| | Fleet Operations Cost (\$/asset) |

Of the FOM's identified above, several can be considered of the highest importance towards directly satisfying customer desires. Spatial and Spectral Resolution are both critical to analyzing scenes of interest. For remote sensing applications seeking high quality images, Spatial Resolution (the size of the smallest discernible object) is the primary concern. For applications which perform more detailed analyses of the chemical or material make-up of scenes, Spectral Resolution is paramount. The responsiveness of a space-based imaging asset can best be captured by the time between a customer's request for an image and its delivery. Such a figure is crucial for customers requiring near-immediate data such as first responders, natural disaster response teams, and most military applications. However, the most important FOM identified is the Revisit Time. This metric which quantifies the time window between successive imaging passes of a particular site is directly related to a system's responsiveness to customer needs as well as the ability to generate high temporal resolution image archives.

Patent Application Activity

The figure below depicts patent application activity in the United States up to 2016 filed under International Patent Classification (IPC) designations relating to space-based remote sensing. These include "G02 – Physics – Measuring; Testing", "G02 – Physics – Optics", "H04 – Electricity – Electric Communication Technique", "B64 – Performing Operations; Transporting – Aircraft, Aviation, Cosmonautics", and others. A noticeable spike has occurred in applications since the early years of the current decade. Top commercial applicants include DigitalGlobe, Boeing, Lockheed, Raytheon, and Planet (combining Planet, Terra Bella, and SkyBox Imaging applications). Boeing, Lockheed, Raytheon and other top assignees do not appear among the space remote sensing companies investigated here since they develop and operate technologies for *terrestrial or airborne* remote sensing. This suggests a difficulty in distinguishing between space-based and airborne applications of remote sensing during patent searches.

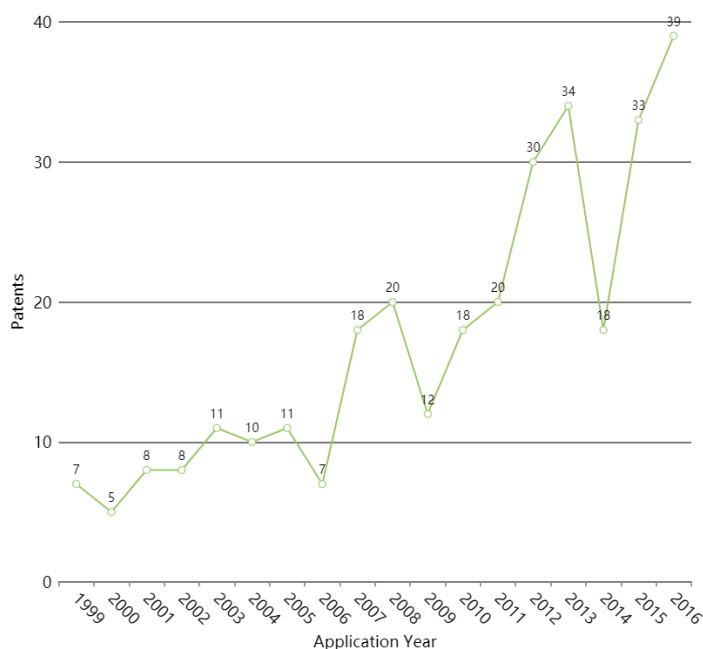


Fig. 7.1.2. Patent application trend for remote sensing-related technologies; the keyword search included logical combinations of "Earth imag*", "Earth observ*", "remote imag*", "remote sens*", "geospatial", "space-based", and "satellite", where * is a wild-card character.

Selected Companies and Associated Product Lines

In generating a list of companies active in the Earth Sensing sub-sector, this analysis relied primarily on the listing of corporations who have been granted a remote sensing license by the Commercial Remote Sensing Regulatory Affairs (CRSRA) office within NOAA's Satellite and Information Services. Per the National and Commercial Space Programs Act, "no person that is subject to the jurisdiction or control of the United States may, directly or through any subsidiary or affiliate, operate any private remote sensing space system without a license." CRSRA's online repository identifies 24 corporations which have been granted such licenses since 2003. Of the 24 companies, several were found to have been awarded remote sensing licenses for non-commercial reasons – such as non-profit research, university projects, or for imaging payloads which may inadvertently image Earth (to abide by regulatory requirements); in addition, clearly defunct corporations were not considered.

A final list of 12 American corporations active in the sector was compiled and is detailed in Table 7.1.2 below along with their major products and their status. They operate, plan to operate, or have retired a total of 21 remote sensing missions. In the "Product Status" column, for constellations, the year of the first launch is indicated. In most cases, data present in the license award notice is supplemented by information found on the corporation's website and in public releases via news articles and statements – these include product names, fleet sizes, and milestone dates. The technologies and capabilities proposed by these companies will be discussed in a subsequent section. It should be noted that any fleet of the same or similar satellites comprised of 4 or more units is considered a constellation.

The scope of this analysis is on those corporations directly involved in obtaining images from space-based assets. Unless they are also directly involved in obtaining remotely sensed data, secondary aggregators and distributors of data are not considered. These may include map and navigation software developers, such as Google (through their Google Earth and Google Maps products) and other Geographic Information Systems (GIS) companies such as Esri. There is an active and lucrative market which is presently being pursued but they are customers, rather than members, of the commercial remote sensing sector. On the other hand, companies such as Planet and Digital Globe which provide analytical products and GIS services based on imagery captured by their own satellites, are included.

Selected Product Timeline

Fig. 7.1.3 below is a timeline of active and proposed products from select companies in the sector. Planet and DigitalGlobe both have plans to refresh their aging fleet of RapidEye, WorldView and GeoEye satellites with new products leveraging the new paradigms of the satellite industry – namely Cubesats and constellations. In addition, most companies with planned products target dates between late 2018 and 2021 at the latest.

Table 7.1.2: Selected Companies and Associated Product Lines

| Corporation | License Award Date | Key Products | Product Status |
|----------------------------|---------------------------------|--|--|
| Astro Digital US, Inc. | 2016; 2016 | Landmapper-BC Constellation; Landmapper-HD Constellation | Active (in progress, 2017); Planned (2018) |
| BlackSky* | 2014; 2018 | Pathfinder 1 Demo mission; 60 Satellite BlackSky Global Constellation | Retired; Planned (2020) |
| Capella Space Corporation | TBD | 36 Satellite SAR Constellation | Planned (TBD); |
| Chandah Space Technologies | 2017 | InsureSat Constellation | Planned (TBD) |
| DigitalGlobe** | 2003; 2004; 2017; 2017 | 4 Satellite Worldview Constellation; GeoEye-1; 6 Satellite Scout Constellation; 6 Satellite Worldview Legion Constellation | Active (2007); Active (2008); Planned (2019); Planned (2021) |
| Orbital Sidekick | 2017; N/A | ISS-based Hyperspectral Earth Imaging System Trial (HEIST); HSI Pathfinder and Constellation | Active (2018); Planned (2019) |
| Planet ⁺ | 2015; 2015; N/A; N/A | 5 Satellite Rapid Eye Constellation; 13 Satellite SkySat Constellation; 175+ Satellite Flock Constellation; 6 Satellite Swift SAR Constellation | Active (2009); Active (2013); Active (in progress, 2014); Planned (TBD) |
| SpaceVR | 2016 | Overview 1 Virtual Reality Imager | Planned (2018) |
| Spire Global | N/A | 60+ Lemur-2 Constellation | Active (in progress, 2015) |
| Teledyne Brown Engineering | 2013 | Multiple User System for Earth Sensing (MUSES) Platform on ISS | Active (2017) |
| XpressSAR | 2015 | 4 Satellite SAR Constellation | Planned (2020) |
| Umbra Lab | N/A | 12 Satellite SAR Constellation | Planned (TBD) |

* BlackSky is a subsidiary of Spaceflight Industries

** DigitalGlobe is a subsidiary of Maxar Technologies

+ Planet Labs, Inc., rebranded as Planet in 2016; acquired SkySat constellation in 2017 after purchase of Google's Terra Bella (formerly Skybox Imaging); acquired RapidEye constellation in 2016 from Canadian company, Blackbridge

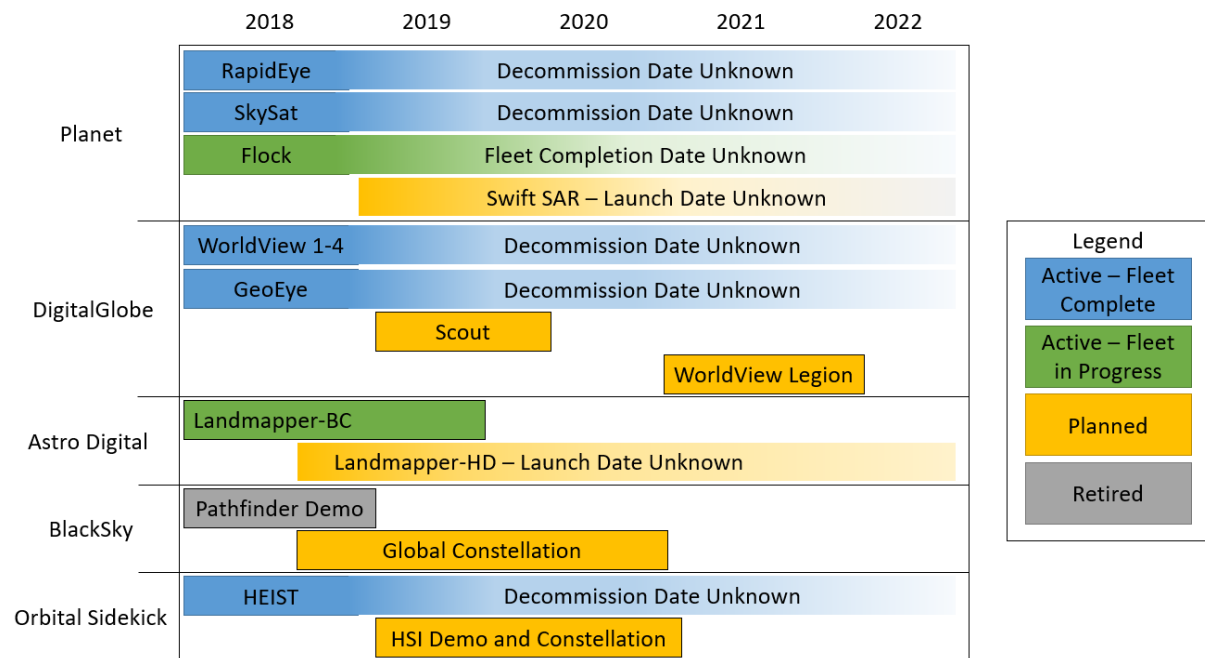


Fig. 7.1.3. Timeline of active and proposed products from select companies in the Earth Sensing sub-sector.

Associated NASA Projects

Many projects in NASA's Earth Science portfolio can be classified as remote sensing. NASA's Earth Observing System Project Science Office (EOSPSO) claims that NASA has carried out 47 Earth observing missions in its past, is presently conducting 28, and has plans for 27 more in the future. These range from one-off experiments like CloudSat and the Soil Moisture Active-Passive (SMAP) mission, to technology demonstration and pathfinder missions such as Earth Observing 1 (EO-1), to premier programs such as Landsat and the Geostationary Operational Environmental Satellites (GOES) series.

The science which motivate these missions require a variety of payloads to study oceanographic, atmospheric, climatological, or geological phenomena. Some payload types developed or improved upon by these missions which are of particular interest to the commercial remote sensing sector include high resolution panchromatic, multispectral, and even hyperspectral imagers as well as synthetic aperture radar hardware and software. Commercial entities have also followed NASA's suit in developing and operating payloads externally mounted to the International Space Station (ISS). NASA's Landsat series of missions is of particular relevance to commercial remote sensing as it has provided millions of moderate-resolution, global coverage Earth images which are freely available to the public. As such, it can be argued that commercial viability of a particular remote sensing architecture is contingent on its ability to deliver a better product than the free Landsat data. Here, "better" can mean a variety of things, as captured by the FOM's discussed in Table 7.1.1 – e.g. more current, higher resolution, more spectrally diverse, etc.

Technologies

Throughout the following discussion of key technologies being employed, developed and proposed in the commercial Earth sensing sub-sector, refer to the "Commercially Active Technology Area Breakdown Structure" section at the end of this report for the mapping of technology numbers to technologies.

Imaging Payloads

Technology Areas: 13.1, 13.2

A majority of American commercial Earth sensing operations occur at least in part in the visible spectrum. Of the identified 21 unique products planned or in operation, 14 image the Earth in visible light. These include 6 panchromatic sensors (like those on DigitalGlobe's WorldView satellites) which capture the combined brightness of the entire visible spectrum in a black and white image, and 10 multispectral sensors (such as those on Planet's SkySat satellites and on the planned BlackSky constellation) which capture discrete spectral bands – some in the visible spectrum such as red, blue and green, and others in the near infrared, shortwave infrared and beyond.

State-of-the-art panchromatic sensing resolutions of nearly 30 cm are demonstrated by the large WorldView satellites; among the companies explored, none propose panchromatic sensors for Cubesat missions. Multispectral imagers (MSI) experience greater use among both traditional and small satellites. The apparent leader in the field of MSI resolution is Planet's SkySat constellation at 1.0 m. BlackSky plans to have a 20 satellite constellation by 2020 with a similar 1.0 m resolution. Interestingly, SkySat's 110 kg small satellites (though not Cubesats), exhibit better MSI resolution than the much larger WorldView or GeoEye satellites which operate between 1.2 and 1.8 m resolution. Cubesat based MSI missions include Planet's active Flock constellation with spatial resolution of 3.7 m and Astro

Digital's Landmapper-HD constellation which proposes industry-leading Cubesat MSI resolutions around 2.2 m by 2018. Fig. 7.1.4 below shows a trend of ground resolutions for remote-sensing systems over the past decade. Notice how, for an assumed altitude and given aperture size (1.1 m for large satellites and 0.2 m for cubesats), satellite systems are approaching fundamental physical limits on possible ground resolution (as determined by the Rayleigh Criterion, based on aperture diameter).

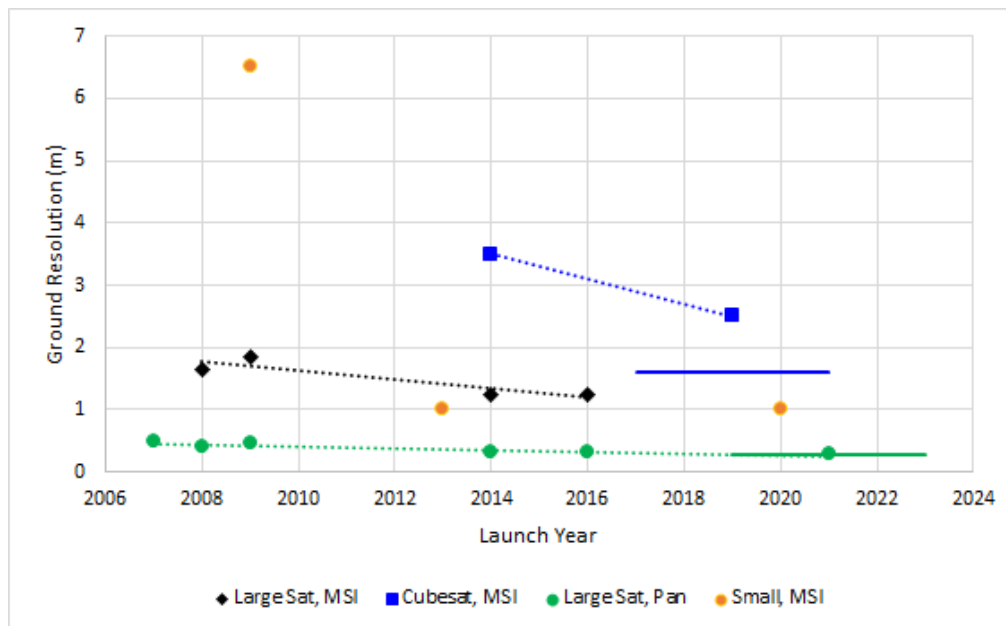


Fig 7.1.4. A comparison of trends in ground resolution (m) for cubesats, small satellites, and traditional large satellites. The solid lines represent aperture-based fundamental physical limits on diffraction-limited ground resolution for a given satellite size at an assumed altitude.

Only two companies have proposed or currently operate hyperspectral imaging (HSI) payloads which capture data at hundreds or thousands of discrete bands across the electromagnetic spectrum. Two ISS mounted commercial payloads demonstrate HSI capabilities: Orbital Sidekick's Hyperspectral Earth Imaging System Trial (HEIST) and Teledyne Brown's Multi-User System for Earth Sensing (MUSES) platform. Orbital Sidekick plans to follow HEIST with a Pathfinder HIS satellite mission in 2019. The latter is host to a non-commercial German hyperspectral imager known as DLR Earth Sensing Imaging Spectrometer (DEIS). While the high data content of HSI sensors has been consistently lauded as extremely valuable, few commercial opportunities have been pursued. This may be due to underdeveloped technologies or the large quantities and sizes of data which HSI payloads produce.

One additional payload type receiving interest in the commercial Earth sensing sector is synthetic aperture radar (SAR). This active imaging technique (and others including LIDAR) have been used extensively in NASA Earth science missions. SAR's technological maturity has led to proposed adoption by as many as 4 remote sensing companies including new players such as Capella Space Corporation and Umbra Lab. Primary benefits of X-band SAR include high-resolution, cloud-penetration, and the ability to operate during nighttime. While no American commercial SAR missions are currently active, they may emerge by 2020. Capella proposes a 1.0 m resolution SAR constellation of up to 36 Cubesats by 2020; Umbra Lab proposes a similar microsat constellation in the near future capable of 0.25 m resolution.

Satellite Subsystems and Ground Systems

Technology Areas: 1.2, 1.5, 5.1, 5.2, 6.1, 6.2, 8.2, 8.3, 10.3, 10.4, 10.5

An Earth sensing endeavor must also design or otherwise obtain a satellite capable of hosting the advanced imaging payloads discussed previously. As such, development and advancements in standard satellite subsystem technologies are important. Particularly important to Earth sensing missions are the on-board computing and communications architectures. For example, high-volume data storage and rapid data downlinking capabilities were identified as key FOM's for the Earth sensing sector's strategic development – these two figures are closely tied to satellite size. In the former case, larger satellites such as WorldView and GeoEye claim between 1 and 3 Tbit storage capacity; similar information is not available for proposed Cubesat missions, but small satellites, like Planet's SkySat can presently store up to 720 Gbits. For communications and downlinking, WorldView and GeoEye operate above 700 Mbps, SkySat at around 500 Mbps, while Astro Digital plans for its Landmapper HD Cubesat to downlink at 300 Mbps. It is expected that in the near-future, downlink capabilities may exceed 1 Gbps. Additional core satellite technologies which companies plan to leverage include: novel small sat propulsion methods such as water based and radio frequency thrusters and green monopropellant motors; fine attitude knowledge and control hardware; and multi-station ground networks for greater downlink capabilities.

Similar improvements are sought in the ground segment of Earth sensing missions. The near-endless stream of data from orbiting assets poses a benefit and a challenge. While not all data is immediately sold to customers, it may be stored in order to build and update archives; this requires large storage capacities (on the order of Petabits) and an efficient data pipeline to satisfy customer requests. Perhaps the most important aspect of the ground segment is the development of advanced and efficient algorithms for data synthesis, post processing and analysis. Companies including Black Sky, Astro Digital and Orbital Sidekick advertise services including change detection, feature detection and identification (including materials and chemicals), multi-modal data synthesis (which fuse data imagery with other data products), and other analytical products based on machine learning and natural language processing. Astro Digital plans to supplement data collection from its own assets with publicly available Landsat imagery for these advanced analytical products.

Cubesats and Constellations

Technology Areas: 10.6, 14.1, 14.2

The high revisit rates demanded by customers is a major driver in an ongoing push towards constellations of Cubesats in Low Earth Orbit (LEO), mostly in Sun Synchronous Orbits. The low cost and high standardization and reproducibility of Cubesats make them ideal for swarms of Earth observing satellites. Fleets can be placed in multiple planes with ~90 minute orbital periods to image most of the Earth quickly. Indeed, 15 of 21 products investigated currently operate or are planning to operate in constellations and at least 6 of these 15 are classified as Cubesats (at least 2 others are classified as small satellites). Most Cubesat constellation operators investigated promise near-daily revisits of customer locations, with BlackSky quoting time from image request to capture at 90 minutes for their planned constellation. Fig. 7.1.5 summarizes the trend in revisit time of selected commercial remote sensing architectures launched in the past decade. Fig 7.1.6 compares refresh rate and ground resolution and notices a general trend of improvement in both FOM's.

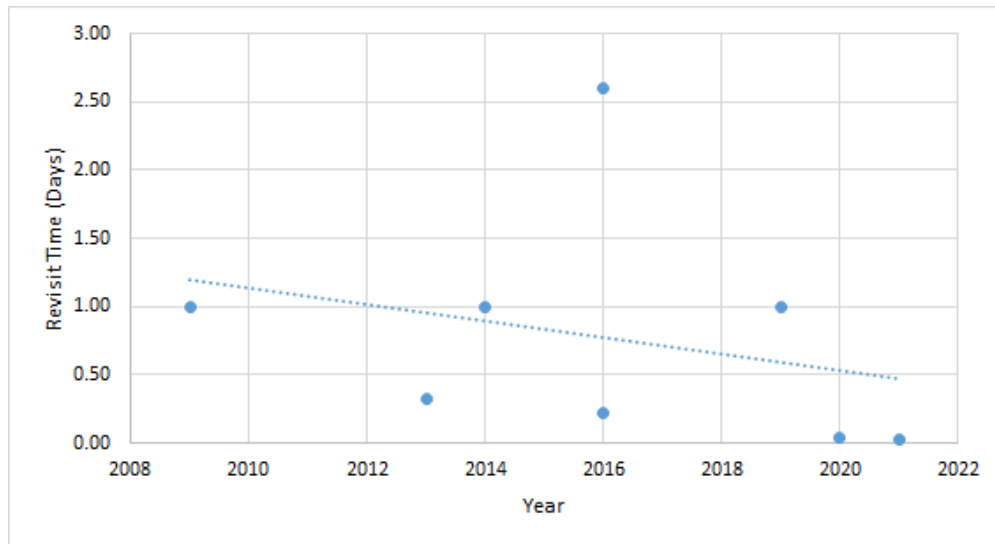


Fig 7.1.5. Revisit times for selected remote sensing satellite architectures of the past decade.

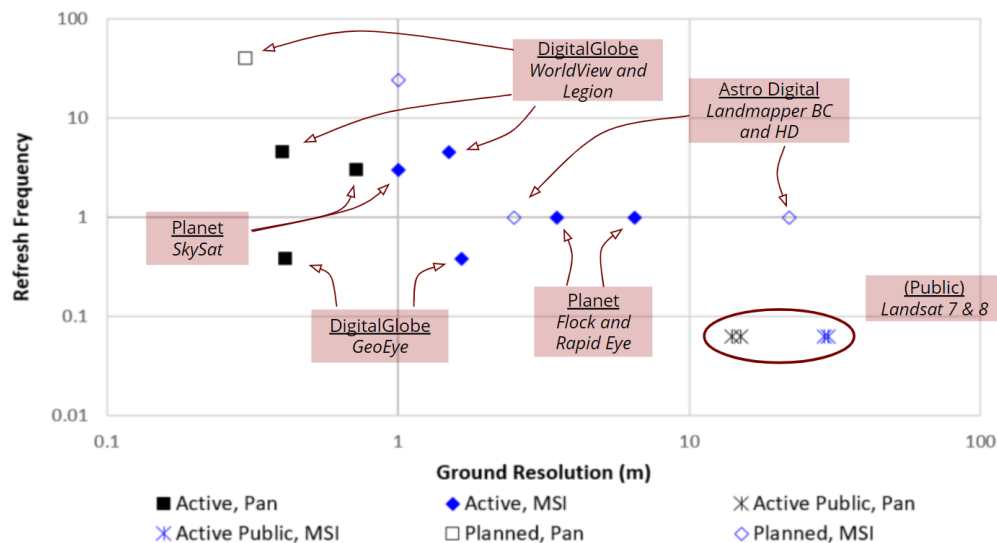


Fig 7.1.6. A two FOM plot showing how ground resolution and refresh rate (shown here as refresh frequency) are related. Note a general trend towards the top and left of the plot, implying that improvement in both FOM's is possible. At the bottom right, publicly available data from Landsat satellites marks the lower end of the performance boundary. This result merely shows how most commercial satellite imaging companies strive to be "better than the free option".

Cubesat missions require the miniaturization of payloads as well as of all other satellite subsystems. Miniaturization particularly impacts those FOM's dependent on size or some characteristic length such as resolution (via aperture diameter) and downlink and on-board storage. In addition, the constellations require ground segments and tracking/control architectures capable of handling large fleets. These capabilities are well demonstrated by Planet's Flock of 175+ satellites as well as Spire Global's Lemur-2 constellation of 60+ Cubesats. Recent developments in launch vehicles intended for large batches of small satellites are promising for low cost and tailored access to LEO.

Key Technology Distribution

Throughout this section, technology numbers refer to those in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report.

This section contains insights on the Earth sensing sub-sector gathered from querying the database of technologies, companies, and products produced as part of this research.

Sector and Status Focus

Figure 7.1.7 below details the usage or development of Level 3 technologies by each of the 21 products active or planned by the 12 companies in the Earth sensing sub-sector. While not explicitly mentioned by all companies, common technologies are required of any space-based imaging platform and include communications and downlinking capabilities, on-board computing requirements, and data storage and distribution. These 10 technologies can be ignored when determining the unique technological contributions of each product. Each product also employs at least one of the technologies in the unique imaging payload section highlighted in the image. Some products may employ more than one of these technologies – a common pairing is panchromatic and multispectral payloads.

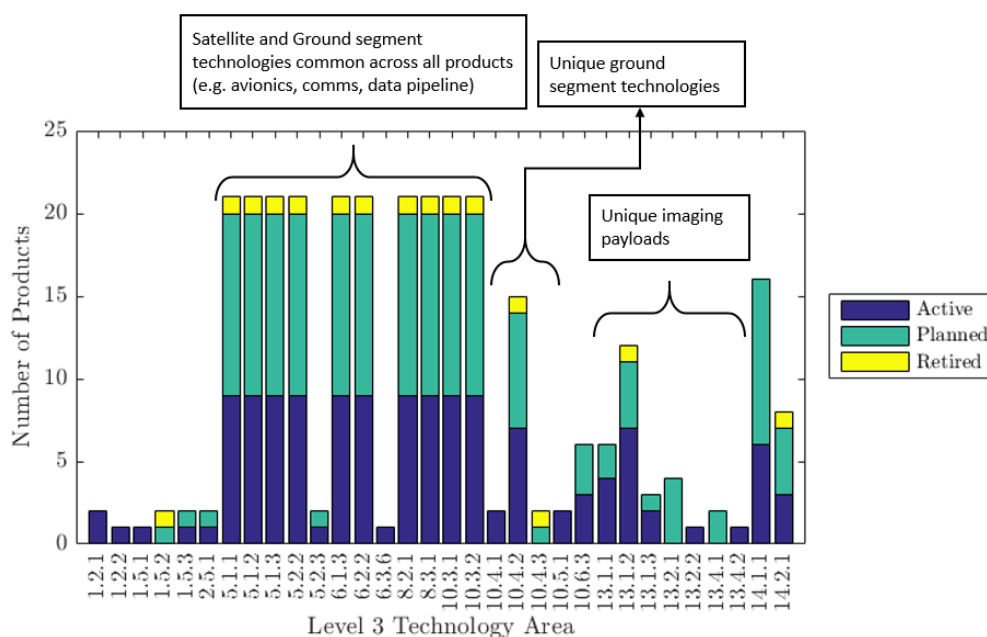


Fig. 7.1.7. Number of Products vs. Level 3 Technology Area broken down by project status. This figure shows how the technology development in the sector is distributed amongst various project statuses, including active, planned, or retired products.

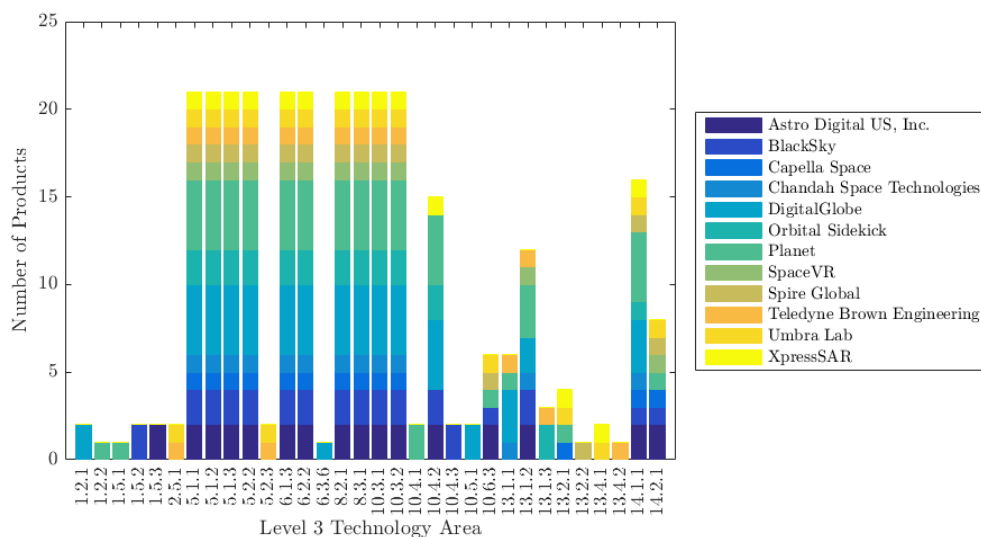
Company Focus

Table 7.1.3 below collects the number of technologies being developed or employed broken down by company. It shows aggregates for each by 1) total instances of each technology for multiple products within the same company and 2) instances of each technology ignoring this multiplicity. Again, for unique technology contributions, the 10 common technologies may be subtracted for each product. Both values shown support conclusions that Planet and DigitalGlobe are the largest and most influential

players in the sector. They both operate multiple products with a variety of imaging capabilities and payloads. For example, with its planned Swift constellation, Planet may soon become the only organization to operate both passive (panchromatic and MSI) and active imaging assets (SAR). However, as BlackSky, Astro Digital, and Orbital Sidekick have demonstrated, the market is still promising for smaller/younger organizations. Fig 7.1.7 breaks down the technology development by product and company.

Table 7.1.3: Organizations with the Highest Number of Technologies under Development

| Organization | Technologies (including multiple products) | Technologies (not including multiple products) |
|----------------------------|---|---|
| Planet | 59 | 20 |
| DigitalGlobe | 57 | 17 |
| Astro Digital US, Inc. | 32 | 16 |
| BlackSky | 31 | 17 |
| Orbital Sidekick | 25 | 13 |
| Umbra Lab | 17 | 17 |
| Teledyne Brown Engineering | 16 | 16 |
| Chandah Space Technologies | 13 | 13 |
| Spire Global | 14 | 14 |
| XpressSAR | 14 | 14 |
| Capella Space | 13 | 13 |
| SpaceVR | 12 | 12 |



them. As expected, the largest companies (e.g. Planet, DigitalGlobe and Spire) seem to have the capital and R&D capabilities to pursue a variety of unique technologies.

Table 7.1.4: Technologies Being Developed by a Single Company

| Level 3 Tech Areas | Organizations |
|----------------------|----------------------------|
| 1.2.1, 6.3.6, 10.5.1 | DigitalGlobe |
| 1.2.2, 1.5.1, 10.4.1 | Planet |
| 1.5.2, 10.4.3 | BlackSky |
| 1.5.3 | Astro Digital US, Inc. |
| 13.2.2 | Spire Global |
| 13.4.2 | Teledyne Brown Engineering |

Product Line Focus

Table 7.1.5 below presents the technologies most widely used or planned. The 10 common technologies are present in all products across all companies. Multispectral imaging is the most widely used imaging payload; also, as discussed previously, Cubesat systems and constellation operations are prolific among active and future products.

Table 7.1.5: Technology Areas Being Developed by Multiple Organizations and Product Lines

| Level 3 Tech Areas | Number of Organizations | Number of Products |
|--|-------------------------|--------------------|
| 5.1.1, 5.1.2, 5.1.3, 5.2.2, 6.1.3, 6.2.2, 8.2.1, 8.3.1, 10.3.1, 10.3.2 | 12 | 21 |
| 14.1.1 | 10 | 16 |
| 10.4.2 | 6 | 15 |
| 13.1.2 | 7 | 12 |
| 14.2.1 | 7 | 8 |
| 10.6.3, 13.1.1 | 5, 4 | 6 |
| 13.2.1 | 4 | 4 |

Conclusion

The remote sensing sub-sector is an active and growing one. Larger and more established companies enjoy powerful and proven fleets of Earth-observing satellites. These systems provide them with the income necessary to develop more advanced successors which incorporate new technologies and capabilities. However, the established players (DigitalGlobe and Planet) are not the only ones in the sub-sector. New and emerging companies such as BlackSky, AstroDigital and UmbraLab are innovating new solutions based on space industry-wide paradigms of Cubesats and constellations. Further, passive imaging is not the only approach being taken; synthetic aperture radar seems to be a promising technology for all-day, all-weather, high-resolution coverage of Earth. Conversely, technologies like hyperspectral imaging, which have long been touted as the future of space imaging, have seen limited adoption in the past decade. This may be due to the high volumes of data and expensive payloads which might not allow business and technology cases to close.

To encourage further growth in the sub-sector, NASA should continue to make advancements (along with its university and industry partners) in the miniaturization of satellite technologies and make these available to any and all space sectors interested in this new paradigm. This naturally leads to further

work in understanding how massive satellite constellations can be most effectively operated and maintained. Lastly, NASA should work with industry partners to further the state and adoption of Artificial Intelligence and smart algorithms; this cross-cutting technology area will be particularly useful in the generation of remote sensing imagery products through change detection, object recognition, and other analysis capabilities.

References

- [1] Ruffner, K.C. *Corona: America's First Satellite Program*. New York: Morgan James, 2011
- [2] Aerospace Industries Association, Bryce Space and Technology. "Engine for Growth: Analysis and Recommendations for US Space Industry Competitiveness", 2017
- [3] Wong, F.c. "Understanding the Revenue Potential of Satellite-based Remote Sensing Imagery Providers." 2005 IEEE Aerospace Conference, 2005.
- [4] Satellite Industry Association, Bryce Space and Technology, "2018 State of the Satellite Industry", 2018

* In addition to these cited sources, information and data on each company's activities was found on publicly available sources including company websites, space news articles, and government reports.

Sub-sector #8.1: Planetary Physical Surveying, Mapping, and Prospecting Services

Sub-Sector Overview

This emerging market sub-sector is comprised of systems and services for the exploration, imaging, sampling, analysis and resource characterization activities on planetary bodies beyond the Earth, for the purpose of identifying economically recoverable concentrations of a wide range of natural resources. The outputs of this sector are of interest to space economy actors who are interested to engage in economic activity in the Space Resource Extraction market sector. This sub-sector has already attracted investment in technology development by the private sector as well as NASA through SBIR's and past science missions to celestial bodies, with most of these activities being in the field of remote sensing and regolith sampling for NASA landers. Based on the stated intent of market participants, future activities in this sub-sector will likely encompass the surveying, mapping and prospecting for economically recoverable resource concentrations via remote sensing, and the verification of characterizations of their composition and distribution via physical sampling. The main output of this sub-sector is the provision of information products which are critical inputs in economic assessments of resource recoverability for the downstream sectors of extraction and processing of water, volatiles, and metals.

Activities in the prospecting and resource characterization sub-sector can span from remote surveys to sample extraction, while data as well as samples may be analyzed in situ, or returned to Earth for in-depth study. The end products delivered to customers are maps and databases of resources and their attributes, such as: spatial and vertical distribution profiles; relative densities; the operating environment including temperature profiles, regolith consistency and atmospheric conditions, and many more. Activities in this subsector are essential precursors to commercial in situ resource utilization (ISRU) activities. The needed capabilities for applications in this sector differ in terms of the type of planetary body and the prospecting strategy employed. Thus, the technology development in this sub-sector, while largely focused on development or adaptation of resource prospecting and characterization systems for the space environment, varies with each company's particular business plan and with their target planetary body. These business plans, in turn, depend on the future demand for in situ natural resources as driven by space agency mission architectures and by the emerging sector of in-space manufacturing.

Sub-Sector Interdependencies

The development of the Planetary Physical Surveying, Mapping and Prospecting Services sub-sector is an essential precursor for the development and growth of the entire Space Resource Extraction sector. As the Space Resource Extraction sector is also the foundation upon which most "space-to-space" business models will be built, this sub-sector is a high priority area for investment and technology development by NASA and the commercial space industry. Activities in this sub-sector are analogous to the essential exploration and resource prospecting activities in the terrestrial economy which inform multi-billion dollar investments and technology development aimed at extracting, processing, and delivering resources to customers.

It is the prospect of imminent development of the downstream commercial extraction and resource processing sub-sectors which will fuel sustained private capital investment in the resource surveying and prospecting sub-sector. Or, in other words, a nascent space economy is required to fuel investment into and growth of a nascent space economy, leading to the conclusion that an external forcing function will be required to start the cycle of growth in the space resources sector. There are two types of exogenous sources of growth which can break through this deadlock and lead to economic expansion in space:

1. Strategic public sector activities, crafted so as to result in the creation of new markets, or
2. Private speculative investment in commercial space ventures, mediated by capital markets.

Strategic Public Sector Activities

Public sector activities benefiting the space resources sector have taken the following forms:

1. Regulating property rights in space [1],
2. The accumulation of a substantial body of science data from Apollo and robotic planetary missions on the distribution and composition of space resources,
3. The selection of Mars Exploration Zones based on their joint potential for science return and in situ resource availability [2]
4. Support for research & development of ISRU concepts through SBIR's and other means,
5. RFP's for the provision of services on planetary surfaces.

The first four activities are long-standing enablers which have benefited this market sector, while the fifth activity represents a significant new opportunity for NASA which has only recently been tapped with the announcement of the Commercial Lunar Payload Services program (CLPS) [3]. Public sector activities are most valuable and impactful when there are large gaps which prevent the closing of business models, which is the case with the Space Resources Sector and this sub-sector in particular. When NASA positions itself as “first customer” for a service which is within reach technologically, such as the COTS and CLPS cases, that can turn out to be the missing piece which closes the business models, leading to substantial commercial space sector investment.

Private Speculative Investment in Commercial Space Ventures

Private investment takes the form of debt and equity investments in commercial, for-profit enterprises, and is undertaken in the expectation of future profit. Crucially, the profit does not have to be imminent for private, speculative investment to materialize. Hence, private investment often emerges when gaps in business models have narrowed to the point where market participants sense imminent lucrative opportunities for investment and are motivated to move quickly so as to acquire a perceived first-mover advantage. Indeed, investment in this sub-sector did emerge in the last decade [4]. However, the anticipated growth and profits have not yet materialized because other interdependent sub-sectors, such as launch, space transportation, in-space manufacturing and space habitation, are all lagging in their development. This led to a number of these early movers experiencing challenges and to a slowdown in the rate of new investment in the sub-sector [5]. Therefore, by directly intervening in ways which narrow the gaps in private sector business models in a cluster of interdependent space economy sub-sectors, the public sector can deliberately target and trigger the birth of new self-sustaining cycles of economic activity which may unlock positive long-term net present value returns for the taxpayer. Once a cycle of economic activity in the space resources sector and its downstream consumer sectors is started by the interplay of these two exogenous forces of public sector strategic interventions and private sector speculative investment, the growth dynamics may transition from mostly exogenous to mostly endogenous, which is one of the necessary conditions for the emergence of self-sustaining

growth in the space resources sector and other interdependent sectors. Fig. 8.1.1 below shows the key input and output (the “Influencers” and “Influences”) of this sub-sector:

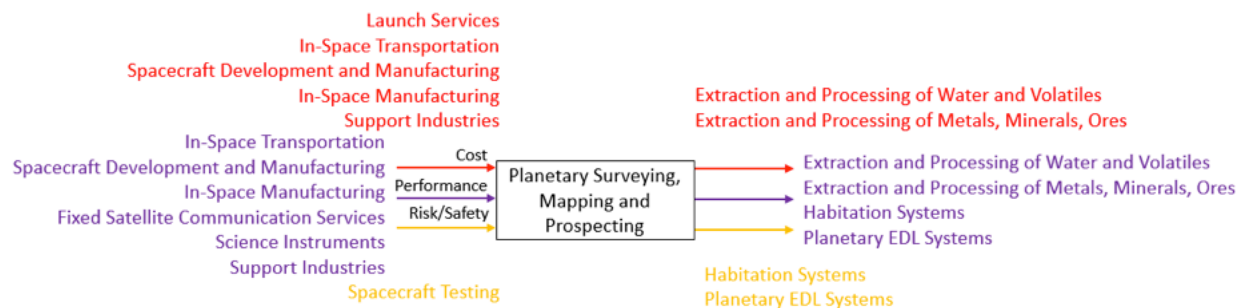


Fig. 8.1.1. Interdependencies between Planetary Surveying, Mapping and Prospecting sub-sector and other market sectors

Strategic Thrust and Figures of Merit

Based on the above overview of the sub-sector, in the context of the broader Space Resources Sector and of its interdependencies with other sectors and sub-sectors, the strategic thrust for the Planetary Physical Surveying, Mapping and Prospecting Services sub-sector may now be stated as follows:

Reducing the cost of acquiring all necessary and sufficient information which directly informs the economic recoverability of space resources from planetary bodies for the purposes of commercial investment in space resource extraction and processing.

The economic foundations for this choice of Strategic Thrust lie in the fact that exploration and prospecting have uncertain outcomes, with some of this uncertainty being inherently irreducible. Beyond a certain point, the high costs of exploration and prospecting combined with this uncertainty stifle private investment in the sub-sector, especially given the context that the prospects of future demand for space resources from downstream sectors are themselves highly uncertain. This analysis leads directly to the derived sub-thrusts and associated figures of merit in Table 8.1.1:

Table 8.1.1: Strategic Sub-Thrusts and Associated Figures of Merit

| Strategic Sub-Thrusts | Figure of Merit (units) |
|-----------------------|---|
| Increasing Resolution | Horizontal Spatial Resolution (m) |
| | Vertical Profile Spatial Resolution (cm) |
| | Vertical Profile Error Rate |
| | Spectral Resolution (# of bands, bandwidth, and color) |
| | Radiometric Resolution (bits) |
| Reducing Cost | Asset Mass (kg) |
| | Economic useful life (years) |
| | Lifetime total ΔV between refilling with Earth-sourced propellant (m/s) |
| | Prospecting Spacecraft Development Cost (\$/unit) |
| | Prospecting Spacecraft Launch Cost (\$/unit) |
| | Prospecting Spacecraft Operations Cost (\$/unit) |

Measuring Performance Improvement

For each product category and/or technology in the Planetary Physical Surveying, Mapping and Prospecting sub-sector, the current state of the art can be recorded against the relevant figures of merit. This provides a baseline for comparison. Targets can be set against each of these by experts in the relevant fields of remote sensing and sampling, following an analysis of technology and market trends.

Increasing resolution, a figure of merit which applies in the remote sensing case, typically requires larger apertures which results in increased mass. However, the proportionality of mass with cost generally holds while the rocket equation still applies, and weakens in the case of refuelable spacecraft. Therefore an interesting strategic direction is the development of prospecting spacecraft with propulsion units which can utilize in situ water, and whose performance can be measured by their lifetime total ΔV they can attain between refilling with Earth-sourced propellant. Such spacecraft can visit multiple targets (different asteroids, or different locations on the Moon or Mars).

Patent Application Activity

Patent application activity in this sub-sector was sparse to non-existent until 2012, which is near the 2010 - 2013 timeframe of the founding of the first asteroid mining companies in the United States (see Fig. 8.1.2). Since then, patent activity has been steady, with the majority of the patents originating in the United States. See Figs. 8.1.3-8.1.4 and their captions for additional insights.

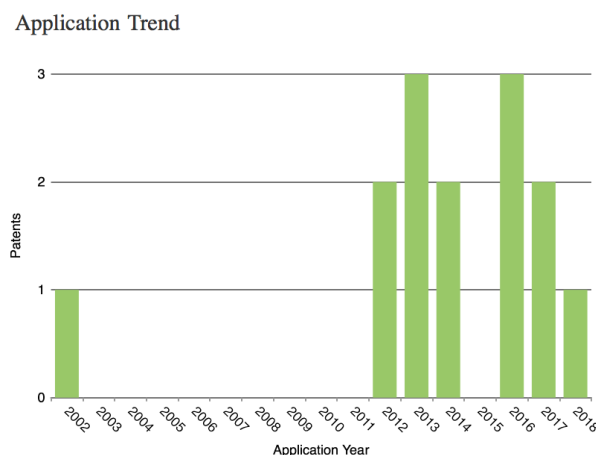


Fig. 8.1.2. Patent application activity for planetary physical surveying, mapping and prospecting. The keyword search used was logical combinations of Mars, Moon or asteroid with mining, resource, ice, water or platinum. The output was filtered by hand to exclude non-space related hits.

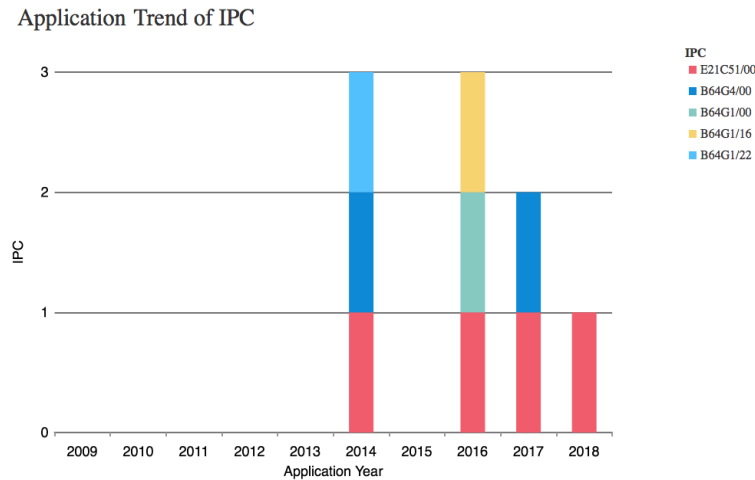


Fig. 8.1.3. Recent patent application activity for planetary physical surveying, mapping and prospecting broken down by IPC (International Patent Classification) area. The most common IPC area was E21C51/00: ‘COSMONAUTICS; VEHICLES OR EQUIPMENT THEREFOR (apparatus for, or methods of, winning materials from extraterrestrial sources)’

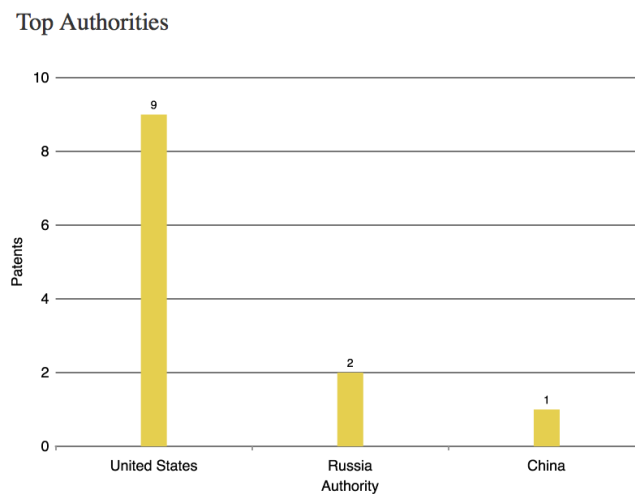


Fig. 8.1.4. Patent application activity by top authorities.

Government Investment

A number of projects have been funded by NASA under Broad Agency Agreements (BAA) tracks 1, 2 and 3 [6]. Projects under BAA Track 1 (light blue, in Table 8.1.2 below) fall within the sub-sector Surveying, Mapping and Prospecting while the remaining projects under BAA Tracks 2 and 3 all fall within Water and Volatiles extraction and processing, as do all the recent SBIR awards under the technology taxonomy of resource extraction. We note that overall, government investment here aligns well with the revealed commercial strategic prioritization in the space resources sector: that is, first invest in prospecting, then invest in water ISRU which assists with reducing the cost of prospecting. As expected, the government is investing more in the sector that is just beyond the horizon (water and volatiles extraction), while the private sector is investing more in the prospecting sub-sector which has a more immediate application from the perspective of investors and entrepreneurs.

Table 8.1.2: Recent Broad Agency Agreements (BAA) for ISRU

| <u>BAA</u> | <u>Awarded to</u> | <u>Technology summary</u> |
|---|-------------------------|---|
| Enhancing lunar exploration with ISRU | Blue Origin | Model lunar volatiles, concentrations; how to utilize |
| ISRU affordability thresholds | ULA | Economic break-even analysis for lunar ISRU propellants |
| ISRU architecture studies | University of Illinois | Integrated ISRU & space logistics optimization |
| NextSTEP-2 ISRU Water Electrolysis | (individuals) | Trade study ISS heritage electrolysis of LH/LOX for Mars |
| Self-cleaning Mars air filter | BlazeTech | Compact, high efficiency self-cleaning Mars air filter |
| H ₂ and CH ₄ Separator for ISRU | Skyhaven Systems | Hydrogen / Methane separator for NASA Mars ISRU |
| ISRU water purification & electrolysis | Paragon | Integrated water purification and H ₂ , O ₂ electrolysis |
| Advanced Alkaline Electrolyzer | Teledyne Energy Systems | Develop electrolysis that can support contaminants expected |
| RedWater | Honeybee Robotics | Coiled tubing to drill through 20m of regolith, then Rodwell for Mars |
| O ₂ & fuel from ISRU on Mars | OxEon energy | Electrolysis stack that produces O ₂ , H ₂ , CO, methanation, CH ₄ |

Table 8.1.3: Recent SBIR Awards for Space Resource Extraction

| Proposal Number | Proposal Title | Firm | Award Amount | Mission Directorate | Center | Year |
|-----------------|---|--------------------------------|--------------|------------------------------------|--------|------|
| T4.02-9821 | Planetary LEGO | Honeybee Robotics Ltd. | \$ 118,690 | Small Business Technology Transfer | KSC | 2017 |
| T4.02-9808 | Regolith to Steel Powder Oxygen; Water with Small Equipment | Rolf Miles Olsen | \$ 124,984 | Small Business Technology Transfer | KSC | 2017 |
| H1.02-9600 | Advanced Mars Water Acquisition System | Pioneer Astronautics | \$ 124,990 | Human Exploration and Operations | JSC | 2017 |
| H8.01-9521 | Microgravity Granular Material Research (MGMR) Facility for ISS | Trans Astronautica Corporation | \$ 124,060 | Human Exploration and Operations | JSC | 2017 |
| H10.03-9438 | Helium and Hydrogen Mixed Gas Separator | Reactive Innovations LLC | \$ 124,917 | Human Exploration and Operations | SSC | 2017 |
| H1.01-9111 | ISRU CO2 Recovery | TDA Research Inc. | \$ 125,000 | Human Exploration and Operations | JSC | 2017 |

Associated NASA Projects

ISRU is an important area of development for KSC's Swamp Works. Innovative designs within the Planetary Physical Surveying, Mapping and Prospecting sub-sector include: RASSOR, for excavating regolith in very low gravity environments; Extreme Access Flyers, which expel jets of in situ sourced gases to maneuver; 'Swarmies', a robot swarm concept to improve the efficiency of resource prospecting; a 'Regolith Bin' ISRU test environment; and an electrostatic dust shield that removed 99% of dust from protected surfaces. We note that all these designs aim to improve the efficiency of the resource prospecting function, thereby aligning with the commercially derived strategic thrust for this sub-sector. Indeed, the most impactful of these efficiency-improving designs, using in situ resources as propellants to increase the total ΔV capability of prospecting spacecraft, is also being pursued by companies in the commercial sector. This in situ refueling capability can significantly reduce the per-unit cost of acquiring surveying, mapping and prospecting data. Future, similar technologies evolved from these will also help to reduce costs in the downstream sectors of water and metals extraction and processing.

Private Investment

The majority of private investment in this sub-sector dates back to the early 2010's when asteroid mining companies were able to raise funding from the capital markets to start developing systems for extraterrestrial resource prospecting and the extraction and recovery of water and precious metals [4]. However, the business models of these companies are being challenged by the fact that other interdependent sub-sectors, including downstream sectors of space resource consumers and the upstream sector of launch services, have not yet matured to the required level, slowing down the path to market for all asteroid mining companies. As of early 2018, several companies in this sub-sector are facing a retrenchment of private capital [5].

Selected Companies and Associated Product Lines

Table 8.1.4: Selected companies active in Planetary Physical Surveying, Mapping and Prospecting with summary of vision, business plans, product lines and stated capability needs

| Company (year founded; turnover; U.S. employees) | | | Vision | Business Plans | Product Lines | Stated Capability Needs |
|--|--------|-----|---|---|---|---|
| Planetary Resources | | | Mine asteroids for water, precious metals | Supply the in- space economy | Arkyd spacecraft | Prospecting by observation; in situ processing |
| 2010 | \$4m | 17 | | | | |
| Deep Space Industries | | | Lower the cost of access to deep space | Serve in-space economy with tech, resources | XPlorer; Comet water-based engine. | Electrothermal water-based propulsion |
| 2013 | \$1m | 12 | | | | |
| Moon Express | | | Lower cost of access to Moon, deep space | Lunar landing, prospecting, water mining | MX Robotic explorer spacecraft | Lunar landing technology development |
| 2012 | \$5.8m | 30 | | | | |
| Shackleton Energy | | | Mining water on Moon to enable space access | Fuel stations supplied from Moon ISRU | VALKYRIE; ORYX; Zaptec transformer | Novel mini-EDL systems; plasma lightning drilling |
| 2007 | TBD | TBD | | | | |
| TransAstra | | | Turn asteroids into refueling stations | Services to space industries | Optical mining; Omnivore thruster | Concentrated solar mining of volatiles |
| 2015 | TBD | 2 | | | | |
| Deltion Innovations | | | | Mining technologies and robotics | RESOLVE on canx. Lunar Prospector | Lunar oxygen and volatile extraction |
| 2013 | TBD | TBD | | | | |
| Honeybee Robotics | | | Robotics for planetary exploration | Space resource mining technologies | TRIDENT drill (TRL 6); many other drills | Drilling, extracting and sampling |
| 1983 | TBD | TBD | | | | |
| Astrobotic | | | Precise planetary missions | Exploration service provider | Peregrine lander; Polaris excavation veh. | GNC/EDL, Exploration, Software, Robot. |
| 2007 | TBD | 16 | | | | |
| Pioneer Astronautics | | | Technologies to advance space program | Service provider to oil & gas cos | RPSEA Green Oil (enhanced oil recovery) | Gasification, reformation, metal processing |
| 1996 | TBD | 9 | | | | |
| CisLunar Industries | | | Processing is missing link in space value chn | In-orbit refining of in space debris | Space Foundry; tugs | Metallurgy in space; robotics; AI; space ops |
| 2017 | TBD | 5 | | | | |

Key Technology Distribution

Throughout this section, technology numbers refer to those in the “Commercially Active Technology Area Breakdown Structure” section at the end of this report.

Sector Focus:

Table 8.1.5 and Figure 8.1.5 below detail the usage or development of Level 3 technologies by each of the products active or planned by the companies in the Planetary Physical Surveying, Mapping and Prospecting sub-sector. The common technologies required are in the areas of drilling and sampling, for the verification of vertical resource distribution profiles, and in remote sensing, for assessments of the spatial distribution of resources of interest. Not all technologies used by complete resource prospecting systems have been included; only the distinctive, differentiating special technologies have been mapped to the products under study.

Table 8.1.5: Technology Areas Being Developed by Multiple Product Lines

| Level 3 Tech Areas | Number of Products |
|---------------------------------------|--------------------|
| 9.7.8, 9.7.9 | 6 |
| 2.1.2, 13.1.2 | 4 |
| 9.7.16 | 3 |
| 6.2.4, 9.7.7, 9.7.10, 9.7.11, 9.7.14, | 2 |

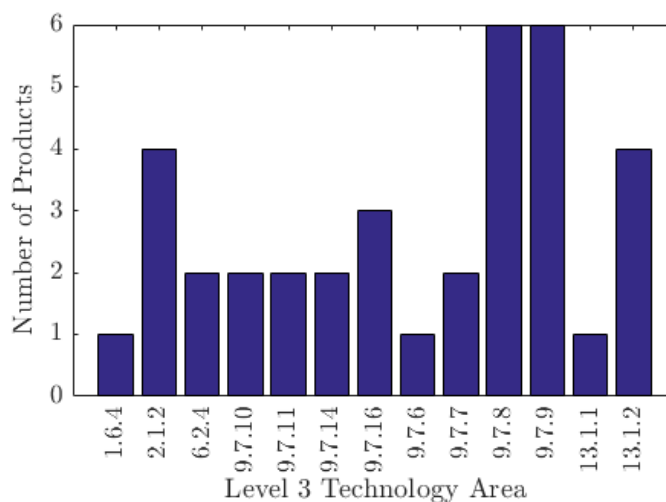


Fig. 8.1.5. Number of Products vs. Level 3 Technology Area. This figure provides a snapshot of the technology distribution in this sub-sector. This includes identifying the range of technology development across the sub-sector, as well as the focus areas of development in the sector.

Company Focus:

Table 8.1.6 below collects the number of technologies being developed or employed by company. It shows aggregates for each by 1) total instances of each technology for multiple products within the same company and 2) instances of each technology ignoring this multiplicity. Also, Fig 8.1.6 breaks down the technology development by product and company. Both support the conclusion that Honeybee Robotics has benefited from the opportunity to develop a number of sampling products in its

collaborations with NASA and JPL for Mars landers and is well positioned at least from a technology portfolio to take advantage of growth and commercial opportunities in this market sub-sector.

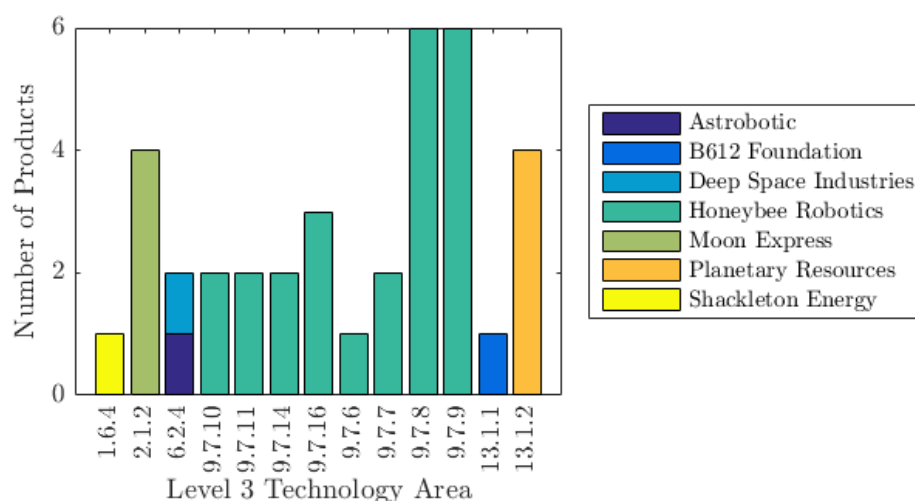


Fig. 8.1.6. Number of Products vs. Level 3 Technology Area broken down by company. This figure shows how technology distribution is broken down by company, and aids in identification of technologies being developed by multiple companies or just a single company, which has implications for the importance of that technology area to the sector as a whole and the confidence with which that technology will be developed by commercial industry.

Table 8.1.6: Organizations with the Highest Number of Technologies under Development

| Organization | Number of Technologies (repeated for multiple projects) | Number of Technologies (not repeated for multiple projects) |
|---------------------|--|--|
| Honeybee Robotics | 24 | 8 |
| Moon Express | 4 | 1 |
| Planetary Resources | 4 | 1 |

Table 8.1.7 below identifies those technologies only being used or planned by one company. While not highly impactful to the rest of the sector, these technologies may improve a company's ability to deliver their products, or may lead to future breakthroughs which turn out to have a significant impact on their sector and on downstream sectors. For example, the performance of the drilling and sampling technologies being pursued by Honeybee Robotics will be critical to the efficiency of future resource extraction activities, a data point which impacts site selection for outposts, habitats and large-scale ISRU facilities. Other technology areas, such as 2.1.2 (3D printed rocket engine components), may be unique to the mission architecture of the organization pursuing them, but are nevertheless important to their own specific business model and to the overall success of their business plan. They can also be important in the mission architecture of other organizations which are active in very different sectors, such as the launch sector in the case of 2.1.2.

Table 8.1.7: Technologies Being Developed by a Single Company

| Level 3 Tech Areas | Organizations |
|--|---------------------|
| 9.7.6, 9.7.7, 9.7.8, 9.7.9, 9.7.10, 9.7.11, 9.7.14, 9.7.16 | Honeybee Robotics |
| 2.1.2 | Moon Express |
| 13.1.2 | Planetary Resources |
| 1.6.4 | Shackleton Energy |
| 13.1.1 | B612 Foundation |

Status Focus:

Of all the technology-product pairs identified in the Planetary Physical Surveying, Mapping and Prospecting sub-sector, the total status distribution is as shown in Fig. 8.1.7 below: 4 active, 22 in development, 7 planned, and 3 retired. The active products are mostly deployed in NASA/JPL missions to Mars, and the products in development are evenly divided between remote sensing and sampling for both asteroid and planetary mining. This is consistent with and reflects the private investment which flowed into this sector since 2010, in pursuit of business models involving the extraction and sale of space resources.

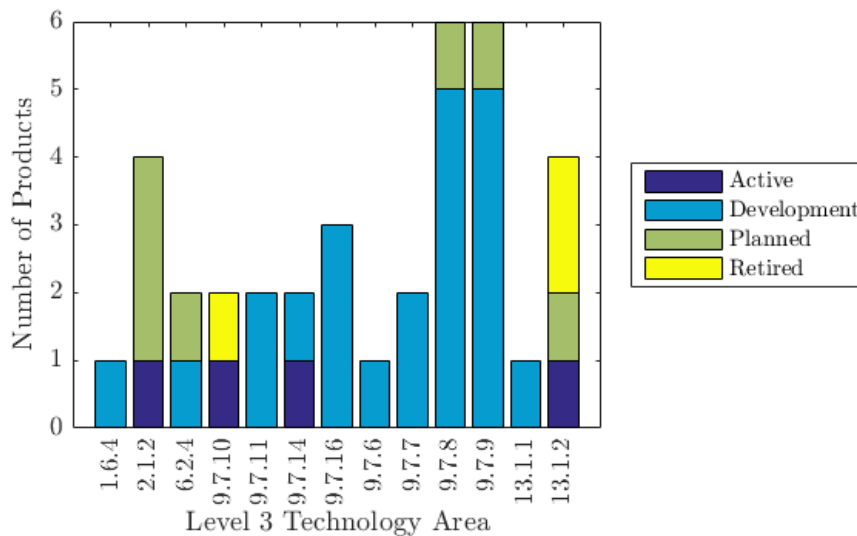


Fig. 8.1.7. Number of Products vs. Level 3 Technology Area broken down by project status. This figure shows how the technology development in the sector is distributed amongst various project statuses, including active, development, planned, or retired products. This allows for evaluation of the sector’s past technology experience and the new technologies into which the sector is pushing with its future products.

Another perspective is to query the CSTR database for Technology Areas in a sub-sector which has no prior retired or active projects, and to group the resulting product-technology pairs by the number of product lines where the technology area is utilized. The hypothesis is that this query may spotlight technologies which are finding more commercial application. In this case, as shown in Table 8.1.7 below, the query is indicating that rotary and percussive drilling technologies (9.7.8, 9.7.9) are found in 6 drill products lines listed in the database, and that downhole sensors embedded on the drill head (9.7.16) are used in 3 product lines.

Table 8.1.7: Technology Areas without Prior Retired or Active Projects

| Level 3 Tech Areas | Number of Product Lines |
|----------------------|-------------------------|
| 9.7.8, 9.7.9 | 6 |
| 9.7.16 | 3 |
| 6.2.4, 9.7.7, 9.7.11 | 2 |
| 1.6.4, 9.7.6, 13.1.1 | 1 |

Product Line Focus:

Figure 8.1.8 below presents the technologies most widely used or planned. Rotary and percussive drilling, multispectral imaging, 3D printed engine components and downhole sensor packages embedded in drill heads are the most commercially active technology areas.

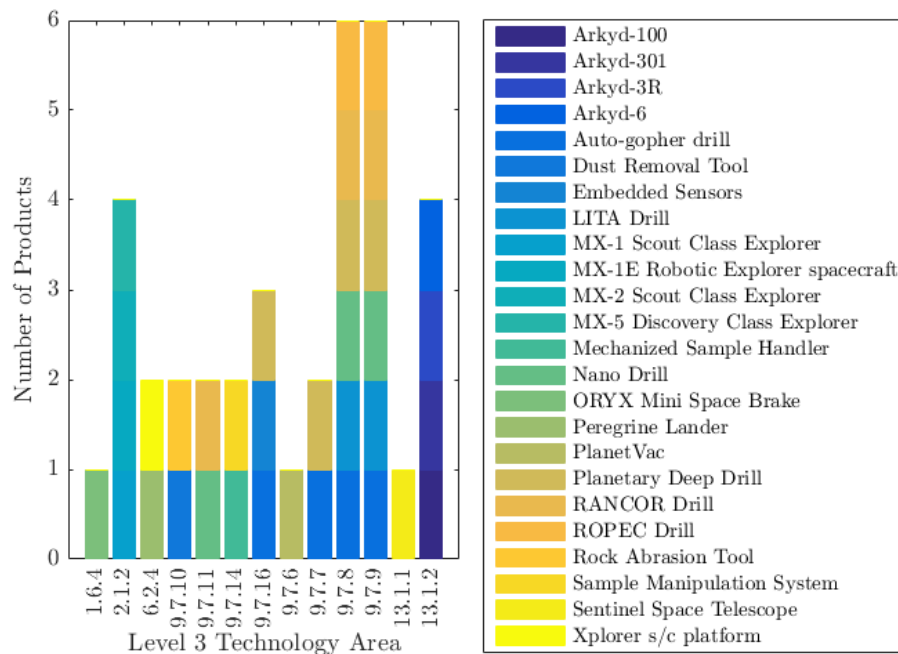


Fig. 8.1.8. Number of Products vs. Level 3 Technology Area broken down by product line.

Conclusions

One lesson learned from the shaky evolution of private investment in the Planetary Surveying, Mapping and Prospecting sub-sector between 2010 - 2018 is that space economy sectors may face adverse development conditions if one sector is in fast investment-led growth mode when other sectors directly connected to it by input / output relationships are moving forward at a significantly slower pace. Hence, a key finding for the acceleration of the development of markets and technologies in space resources is that *groups of interdependent space resource sectors should be targets for simultaneous strategic investment and support by NASA*. In this way, the commercially owned and operated interdependent space economy supply chains that need to be created will all enjoy simultaneous tailwinds of emerging markets for their products as well as ready suppliers for their inputs. This increases the likelihood that interdependent sectors will attract private investment and attempt to grow at the same time, thereby increasing the probability that all investments will be successful.

For example, if the commercial extraction of lunar water and volatiles were to be somehow proceeding in parallel with the development of lunar landers which are capable of refueling, then landers can deliver the ISRU equipment and the ISRU systems can resupply the landers, setting up a mutually beneficial value exchange that can breathe life into the business models of different operators who are interested in different supply chains, thus maintaining the support of their investors long enough for a critical mass of cislunar space markets to emerge.

More generally, this study of the Planetary Surveying, Mapping and Prospecting sub-sector indicates that CSTR sectoral case studies should not be used to identify single sectors or single technologies for prioritization. Instead, studies of several interdependent sub-sectors should be undertaken with a view to the strategic planning for support of *clusters of sub-sectors and their associated technologies*, where clustering is determined by the degree of economic and technological interdependence.

Limitations

This case study of the Planetary Surveying, Mapping and Prospecting sub-sector and associated Space Resources sub-sectors had not been fully completed as at the end of the contract period for this report. Specifically, sector 8 products identified and catalogued in the CSTR database are only those publicly advertised by the companies identified. The products list is therefore not exhaustive. Furthermore, the products identified have not been fully decomposed into and linked to their constituent technologies; only the critical technologies associated with primary value delivery have been catalogued and linked to products in this sub-sector. Hence, the technology-product mappings for this sector are not exhaustive.

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* In addition to these cited sources, information and data on each company’s activities was found on publicly available sources including company websites, space news articles, and government reports.

Commercially Active Technology Area Breakdown Structure

In order to identify technology needs in the various market sectors, a technology breakdown structure was developed and is presented below. At first glance, using the NASA Technology Roadmap technology area breakdown structure would appear to have been satisfactory. However, this categorization of technology areas inherently considers NASA, rather than industry, needs. Furthermore, the existing breakdown is built up from known technology areas, rather than flowed down from strategic thrusts and solution-independent capability needs, which can limit the ability to capture creative new approaches developed by industry to solve aerospace challenges. For this reason, the new technology breakdown below was developed to accurately capture the activities performed by a diverse set of commercial enterprises. This technology breakdown was formed by abstracting from the particular technologies used by companies active in the various sectors. Thus, the technology breakdown below was slowly built up as market sectors were sequentially analyzed. This technology breakdown would be expanded as each subsequent sector is analyzed, as well as when new technologies are developed by existing players in the market or by new entrants into the space economy. To maintain compatibility and facilitate analysis, the technology database structure enables conversion between the existing NASA technology breakdown and the new commercially active technology breakdown presented below.

| Level 1 | | Level 2 | | Level 3 | |
|---------|--------------------|---------|---------------------|---------|--------------------------------------|
| 1 | Propulsion Systems | 1.1 | Liquid Cryogenic | 1.1.1 | LOX_RP1 |
| | | | | 1.1.2 | LOX_LH2 |
| | | | | 1.1.3 | LOX_LCH4 |
| | | 1.2 | Liquid Storable | 1.2.1 | Hydrazine Monoprop Propulsion |
| | | | | 1.2.2 | High Performance Green Propulsion |
| | | 1.3 | Solid | 1.3.1 | Launch Escape Motor |
| | | | | 1.3.2 | Upper Stages |
| | | | | 1.3.3 | Booster |
| | | 1.4 | Gas Storable | 1.4.1 | Cold-gas Thrusters |
| | | 1.5 | Electric Propulsion | 1.5.1 | Blowdown Xenon resistojet |
| | | | | 1.5.2 | Water-based Electrothermal Thrusters |
| | | | | 1.5.3 | Radio Frequency Thrusters |
| | | 1.6 | Other | 1.6.1 | Hypersonic Retropropulsion |
| | | | | 1.6.2 | Modularized Propulsion System |
| | | | | 1.6.3 | Air-Launched Propulsion System |
| | | | | 1.6.4 | Aerobraking and Aerocapture |
| | | 1.7 | Reusable Systems | 1.7.1 | Propulsive Landing |
| | | | | 1.7.2 | Splashdown |
| | | | | 1.7.3 | Air-Capture |

| | | | | | |
|---|-----------------|-----|--------------------|-------|---|
| 2 | Structures | 2.1 | Metallic | 2.1.1 | Propellant Tanks |
| | | | | 2.1.2 | 3D Printed Engine Components |
| | | | | 2.1.3 | ISM/AM optimized structures |
| | | 2.2 | Composite | 2.2.1 | Solid Motor Casings |
| | | | | 2.2.2 | Propellant Tanks |
| | | | | 2.2.3 | Fairing |
| | | | | 2.2.4 | Delta-Wing |
| | | | | 2.2.5 | ISM/AM optimized structures |
| | | 2.3 | Other | 2.3.1 | Multi-Segment Stacking |
| | | | | 2.3.2 | High Specific Strength Structures |
| | | | | 2.3.3 | In-space assembly/expandable optimized structures |
| | | | | 2.3.4 | Microgravity optimized structures |
| | | | | 2.3.5 | Vibration isolation |
| | | | | 2.3.7 | Fairing Recovery |
| | | 2.4 | Reusable Systems | 2.4.1 | Landing for Reusability |
| | | 2.5 | Interfaces | 2.5.1 | Payload Platforms on Existing Infrastructures |
| 3 | Mechanisms | 3.1 | Deployment | 3.1.1 | Landing Legs |
| | | | | 3.1.2 | Landing Fins |
| | | 3.2 | Separation | 3.2.1 | Launch |
| | | | | 3.2.2 | Stage Separation |
| | | | | 3.2.3 | Fairing |
| | | | | 3.2.4 | Spacecraft Deploy |
| | | 3.3 | Interfaces | 3.3.1 | Mechanical Interfaces |
| 4 | Thermal Control | 4.1 | Cryogenics | 4.1.1 | Cryogenic Storage |
| | | 4.2 | Heating | 4.2.1 | Furnaces |
| 5 | Avionics | 5.1 | On-Board Computing | 5.1.1 | High Volume Data Storage (Gigabits to Terabits) |
| | | | | 5.1.2 | System Maintenance, Health Monitoring and Command Execution |
| | | | | 5.1.3 | Error-limiting Downlink Encoding and Modulation |
| | | | | 5.1.4 | GPS-based Timekeeping |
| | | 5.2 | Systems | 5.2.1 | Modularized Avionics |
| | | | | 5.2.2 | Radiation Hardened Electronics |
| | | | | 5.2.3 | Plug-and-play Payloads |
| 6 | GNC and ADCS | 6.1 | Actuators | 6.1.1 | Aerodynamic Control Surfaces |
| | | | | 6.1.2 | Reaction Control |
| | | | | 6.1.3 | Attitude control |
| | | 6.2 | Sensors | 6.2.1 | Inertial Measurement |

| | | | | | |
|---|----------------|-----|-----------------------------------|--------|---|
| | | | | 6.2.2 | Fine Attitude Sensors |
| | | | | 6.2.3 | Timekeeping and time distribution |
| | | | | 6.2.4 | Relative and proximity/differential navigation |
| | | 6.3 | Software | 6.3.1 | Landing Control Laws |
| | | | | 6.3.2 | Simultaneous Multi-Booster GNC Laws |
| | | | | 6.3.3 | Ram-facing control |
| | | | | 6.3.4 | Maintaining microgravity orbit free of perturbations |
| | | | | 6.3.5 | Rendezvous and Proximity Operations |
| | | | | 6.3.6 | Rapid ADC Solutions (for Targeting, Slewing and Pointing) |
| | | | | 6.3.7 | Virtual relative position services |
| | | | | 6.3.8 | Auto Precision Formation Flying |
| 7 | Power | 7.1 | Energy Storage | 7.1.1 | High Specific Energy Batteries |
| | | 7.2 | Power Management and Distribution | 7.2.1 | Power Transmission over Optical Fiber |
| | | | | 7.2.2 | Miniature electronic transformer |
| 8 | Communications | 8.1 | Hardware | 8.1.1 | Communications |
| | | 8.2 | Ground Stations | 8.2.1 | Multi-Station Networks |
| | | 8.3 | Systems | 8.3.1 | High Data Rate Downlinking (Mbps to Gbps) |
| 9 | Manufacturing | 9.1 | Formative | 9.1.1 | Metals |
| | | 9.2 | Subtractive | 9.2.1 | Plastics |
| | | | | 9.2.2 | Metals |
| | | | | 9.2.3 | Advanced Manufacturing Technology |
| | | 9.3 | Additive | 9.3.1 | Plastics |
| | | | | 9.3.2 | Metals |
| | | | | 9.3.3 | Electronics |
| | | | | 9.3.4 | Biological |
| | | | | 9.3.5 | Multi-Material |
| | | | | 9.3.6 | Composites |
| | | 9.4 | Material Processing | 9.4.1 | Deposition (CVE, MBE, etc.) |
| | | | | 9.4.2 | Optical Fiber Preform Pulling |
| | | | | 9.4.3 | Polymerization |
| | | | | 9.4.4 | Crystallization |
| | | | | 9.4.5 | Semiconductor Wafer Healing |
| | | 9.5 | Recycling | 9.5.1 | Plastics |
| | | | | 9.5.2 | Metals |
| | | | | 9.5.3 | Electronics |
| | | 9.6 | Inspection | 9.6.1 | Advanced Inspection Technology |
| | | | | 9.6.2 | Topography mapping |
| | | | | 9.6.3 | Stereo-optic imaging metrology |
| | | 9.7 | In-Situ Resource Utilization | 9.7.1 | Resource extraction and fabrication |
| | | | | 9.7.10 | Abrasive drilling |

| | | | | | |
|----|----------------|------|--------------------------------------|--------|---|
| | | | | 9.7.11 | Coring drilling |
| | | | | 9.7.12 | Optical mining |
| | | | | 9.7.13 | Thermal drilling |
| | | | | 9.7.14 | In-situ analysis and sample processing |
| | | | | 9.7.15 | Membrane shield resource separation |
| | | | | 9.7.16 | Drill-head embedded sensors |
| | | | | 9.7.17 | High-temperature electrodes fabrication for solid oxide electrolysis |
| | | | | 9.7.18 | Robotic rover drivetrain components (for mining rovers) |
| | | | | 9.7.2 | Construction with in-situ material |
| | | | | 9.7.3 | Deployable Mini-Probes for Asteroid Resource Prospecting |
| | | | | 9.7.4 | Concentrated solar thermal mining |
| | | | | 9.7.5 | Integrated gas traps for dilling / resource extraction |
| | | | | 9.7.6 | Pneumatic sample acquisition |
| | | | | 9.7.7 | Wire-line drilling |
| | | | | 9.7.8 | Rotary drilling |
| | | | | 9.7.9 | Percussive drilling |
| | | 9.8 | Assembly | 9.8.1 | Fittings |
| | | | | 9.8.2 | Welding |
| | | | | 9.8.3 | Riveting |
| 10 | Ground Segment | 10.1 | Launch Sites | 10.1.1 | Flying Platform "Ground Support Equipment" |
| | | | | 10.1.2 | Private Launch Sites |
| | | 10.2 | Landing Sites | 10.2.1 | Water-based Landing |
| | | | | 10.2.2 | Ocean Vessel Landing Pads |
| | | | | 10.2.3 | Ground-based Landing Pads |
| | | | | 10.2.4 | Air-based Recovery |
| | | | | 10.2.5 | Runways |
| | | 10.3 | Data Pipeline | 10.3.1 | High Capacity Data Archiving (Petabits) |
| | | | | 10.3.2 | Low Latency Distribution of Data to Customers |
| | | 10.4 | Data Analysis and Product Generation | 10.4.1 | Image Correction |
| | | | | 10.4.2 | Machine Learning for Smart Detection of Change and Features in Remote Sensing in Data |
| | | | | 10.4.3 | Multi-modal Data Synthesis |
| | | 10.5 | Mission Operations | 10.5.1 | Direct Tasking and Downlink from/to Customer Platforms |
| | | 10.6 | Launch Customer Accommodations | 10.6.1 | High Flexibility Customer Accommodations |
| | | | | 10.6.2 | Small Satellite Tailored Accommodations |
| | | | | 10.6.3 | Large Batch Small-Sat and Cube-Sat Launchers |
| | | 10.7 | Launch | 10.7.1 | Off-pad Payload Fairing Encapsulation |

| | | | | | |
|----|--|------|--------------------------|--------|---|
| | | | Preparation | | |
| | | 10.8 | Launch Countdown | 10.8.1 | Rapid Launch Pad Rollout |
| | | | | 10.8.2 | Multi-Core Engine Startup |
| 11 | Environmental Control and Life Support Systems | 11.1 | Air Revitalization | 11.1.1 | Fume Containment |
| | | | | 11.1.2 | Particulate Filtering |
| | | 11.2 | Sterilization | 11.2.1 | Dry heat sterilization |
| 12 | Robotics and Autonomy | 12.1 | Manipulators | 12.1.1 | Robotic Arms |
| | | 12.2 | End Effectors | 12.2.1 | Fabrication |
| | | | | 12.2.2 | Inspection |
| | | | | 12.2.3 | Assembly |
| 13 | Payloads | 13.1 | Passive Observation | 13.1.1 | Sub-meter Resolution Panchromatic Imaging |
| | | | | 13.1.2 | Near Meter Resolution Multispectral Imaging |
| | | | | 13.1.3 | High Spectral Resolution Hyperspectral Imaging |
| | | 13.2 | Active Observation | 13.2.1 | Near Sub-meter Synthetic Aperture Radar |
| | | | | 13.2.2 | Atmospheric Measurements via Radio Occultation |
| | | 13.3 | Non-Earth Remote Sensing | 13.3.2 | Mid-Wave Infrared Imaging Sensor (MWIR) |
| | | 13.4 | Operations and Systems | 13.4.1 | Multi-Mode Payload Operations |
| | | | | 13.4.2 | Hosting of Modular Payloads |
| 14 | Cross-Cutting Technologies and Paradigms | 14.1 | Satellite Operations | 14.1.1 | Constellations - Coherent and Cooperating Fleets of 4+ S/C |
| | | 14.2 | Satellite Design | 14.2.1 | Cube-Sats - Miniaturized, Low Cost, Standardized Satellite Subsystems |